FRAUNHOFER INSTITUTE FOR MATERIAL FLOW AND LOGISTICS, IML

FUTURE CIRCULAR COLLIDER LOGISTICS STUDY

Final Report
Version 1.0 | 12.03.2018

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Executive Summary

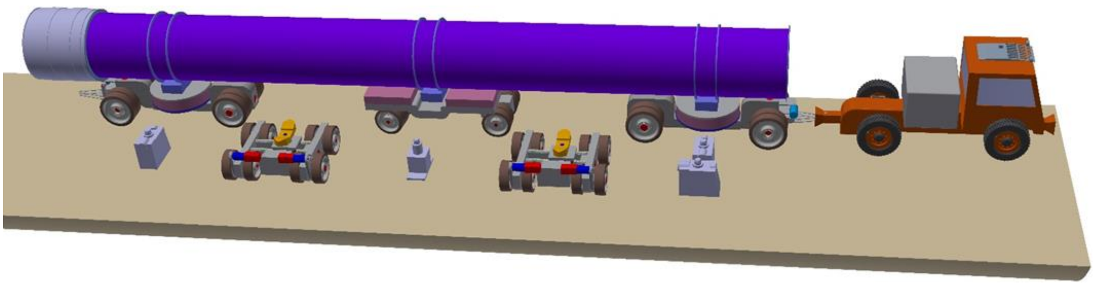
Logistics is of great importance for the construction, assembly and operation of the FCC. During the planning, construction and assembly of LHC, logistics proved to be one of ten key factors behind its success. For the planning of FCC, several logistics aspects were analysed or discussed:

1. Supply strategies for FCC cryo-units;
2. Locations for the storage, assembly and testing facilities;
3. Transport scenarios for cryo-units, including the analysis of stresses and the possibility of intercontinental transport;
4. A design concept for a special purpose vehicle for the underground transportation and handling of cryo-units;
5. Supply scenarios considering the overall FCC construction schedule.

Different supply strategies for FCC cryo-units: The construction of FCC entails high demands for materials that need to be installed. As the construction timeframe for FCC is very tight and available space for material storage on site is limited, it is very important to have effective on-site logistics and a suitable supply chain strategy. Since the final set-up of cryo-units, detectors and even the tunnel layout have not been fixed yet, it is not possible to design a suitable supply chain structure yet. However, as there still isn’t any suitable infrastructure for producing cold mass and cryostats at CERN, carrying out the complete production, assembly and testing of cryo-units by CERN does not seem to be a valid solution due to the high costs which would be incurred for providing the necessary infrastructure. It is thus favourable to distribute the value adding processes amongst third partners. Considering the high-quality requirements for the magnets, a complete outsourcing of the processes is inconceivable. Currently there are no suitable suppliers on the market which offer these products or components. As CERN has process knowledge gained from constructing the LHC and the technological knowledge from engineering components for FCC, it is clear that CERN and any future supplier must collaborate with each other. There could be different levels of supplier integration here.

Selection of possible locations: From an organisational perspective and due to the availability of space, it is preferable to have one single location for assembling and testing magnets. This facility should be located near shaft A and close to the existing CERN facilities. One single shaft is also sufficient for transporting the fully assembled cryo-units into the underground tunnel. Shaft A could be used for lowering the cryo-units into the tunnel. However, it makes sense to have an additional second shaft for lowering the cryo-units, e.g. shaft E, that could serve as a backup in case of any disruptions. Starting from these shafts, the assembled cryo-units will be distributed along the tunnel by means of an underground transportation system. In this way, surface transports over longer distances between shafts can be avoided.

Various transport scenarios: The following transport chain is suggested for the intercontinental transportation of cryo-units or components: Truck transport of goods from origin to the nearest sea port, ship transport to either Rotterdam or Marseilles, and finally truck transport from one of the two sea ports to CERN or as an alternative, barge transport from Rotterdam to Basel or Marseilles to Mâcon and then via truck to CERN.



Design concept for a special purpose vehicle: In the context of this report a concept study was carried out for a special purpose vehicle for the transport and handling of FCC cryo-units in the tunnel. The concept is based on the assumption that cryo-units are lowered in sequence into the tunnel via a shaft and onto the vehicle. The vehicle then transports the cryo-unit to the planned installation location within the tunnel ring. At the installation site special handling equipment is used to transfer the cryo-unit to the exact mounting position. In addition, a “watchdog” concept will be introduced, where an additional vehicle is placed at the front of the transport convoy to ensure transport safety and higher velocities and as an emergency concept in case one of the special vehicles gets damaged and blocks the tunnel.

Suitable supply scenarios: In order to deliver FCC construction in time, both central and decentral strategies are possible. A central approach offers advantages in terms of costs and quality but has disadvantages in terms of process robustness. A central shaft, e.g. shaft A, in close proximity to the CERN area, allows assembly and testing facilities to be centralized and existing infrastructure to be re-used for FCC. Furthermore, necessary storage capacities for tested magnets can be provided in the CERN area. From a qualitative perspective, central supply is favoured as well, as it provides similar testing circumstances for all magnets and short transport routes for tested magnets on public roads. But central supply with only one shaft could lead to disruptions. For example, whenever the transport crane fails, all installation works will have to stop. Therefore at least one second shaft is needed as a backup to prevent the risk of such blockages. In all probability it will not be possible to catch up on any delays in the construction schedule resulting from cryo-unit supply since installation teams must be highly trained and capacities cannot be increased ad-hoc. However, central assembly and testing facilities combined with a number of magnet transport shafts that are spread out geographically, will result in long distance surface transportation that could negatively influence product quality. So, decentral facilities would need to be set up at the shafts. The favoured solution is to locate one shaft at the CERN area with a second shaft on the opposite side of the ring. The solution currently favoured by CERN which envisages distributed supply via four shafts is not recommended. This alternative is very robust in case there are any disruptions but would also mean a lot more infrastructure is required. Besides, the same quality standards need to be guaranteed throughout all facilities so the organisational effort would be increased in this scenario as well.

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Introduction

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research CERN in Geneva is the largest and most powerful collider in the world. CERN and its research and experimental infrastructure is not only a focus for the science community but is also very much in the public eye. With the Future Circular Collider (FCC) Study, CERN has begun to examine the feasibility of a new underground accelerator ring with a length of approximately 100 kilometres.

Logistics is of great importance for the construction, assembly and operation of the FCC. During the planning, construction and assembly of the LHC, logistics proved to be one of the key factors. As the FCC is even larger than the LHC, logistics will also become more and more significant. This report therefore shows new concepts, methods and analytics for logistics, supply chain and transport concepts as part of the FCC study.

This report deals with three different logistics aspects for the planning and construction phase of FCC:

1. A discussion of different supply strategies (including decisions concerning insourcing or outsourcing value added processes) for FCC production of cryo-units (see Chapter 1);
2. A selection of possible locations for the storage, assembly and testing facilities for cryo-units around the FCC tunnel (see chapter 2);
3. A design concept for a special purpose vehicle for the underground transportation and handling of cryo-units (see chapter 3).

Based on the results of these three tasks, chapter 4 describes an analytical evaluation of suitable supply scenarios considering the overall FCC construction schedule as well as varying process times for assembling and testing cryo-units. In addition, the feasibility of various transport scenarios was investigated to assure that the tested cryo-units are transported properly to their final installation point in the FCC. This evaluation aims to provide an in-depth input of the capacities required for assembly and testing facilities, storage and transport at CERN throughout the whole construction phase.

About Fraunhofer IML

The Fraunhofer-Institute for Material Flow and Logistics IML is recognised throughout the world as a top address for integrated, interdisciplinary, networked logistics and supply chain management. The various departments at Fraunhofer IML cover all the fields and skills required to fulfil the wide-ranging and comprehensive tasks required in the context of this study. In these innovative fields, Fraunhofer IML has already carried out fundamental and outstanding work in numerous initiatives, research projects and industry projects. This includes the »Internet of Things«, which has essentially been developed by Fraunhofer IML for logistics and implemented in many successful projects in accordance with the guidelines for »Efficiency enhancement through autonomization«, and »Industry 4.0«.

1 Assembling and testing cryo-units

1.1 General information about FCC construction and cryo-units

1.1.1 FCC construction schedule

The current construction plan and schedule assume the total length of the tunnel to be 97,75 km and a total construction time of 16 years and 2 months (start: 07.05.2027; end: 16.07.2043). Tunnel construction works are planned to take place from February 2028 to December 2033. The outfitting process will take place subsequently (see construction schedule):

- General infrastructure (lifts),
- Survey of underground network,
- Transmission line, EL general services, piping, test piping, ducts, Cryogenics Distribution Line, QRL test, tunnel marking out
- Transportation and installation of the cryo-units,
- Connecting the cryo-units,
- Cryo cool-down and
- Sector test.

Constructing and testing the FCC are planned to be finished in July 2043 and then FCC will be ready to start.

The construction of FCC involves installing large amounts of material. As the construction time for FCC is very tight and available spaces for material storage on site are limited, logistics is very important. Due to their dimensions and weight, the magnets or cryo-units represent a major challenge for FCC logistics, especially for the dipole magnets. That is why the logistics relating to FCC dipole magnets is the focus of this study. **Table 1-1** presents relevant numbers of dipole and quadrupole magnets for FCC logistics:

Table 1-1: Overview of FCC magnet demand and attributes relevant to logistics

Magnet types	Dipole magnet	Quadrupole magnet
Number of magnets	4,800	600
Weight	60 tons	Less than dipole*
L / W / H	13.4m x 1.5m x 1.64m.	Less than dipole*

(* The weight and dimensions of the quadrupole magnets are smaller, so for the sake of simplification the information given for the dipole magnet is taken into account for all magnets in the study.)

1.1.2 Value added processes in cryo-unit production

Before installing the cryo-units, various processes need to be executed to assure the units are of high quality. The process chain comprises the following tasks (see Figure 1-1). After the final test of the cryo-units they will be stored or transported to the FCC cryo-unit transport-shaft and lowered into the tunnel. They are brought to their individual installation point by means of special tunnel transport vehicles.

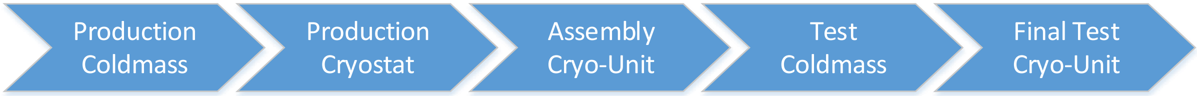

Figure 1-1: Value adding processes for cryo-unit production (without transportation and storage steps)

To develop an integrated concept for the logistics of the cryo-units, the following requirements should be considered:

- The weight of cryo-units means there are special requirements regarding the transportation of such heavy loads as well as for the handling equipment and transport permissions.
- The dimensions of cryo-units mean they cannot be transported in a 40 ft-standard container (L/W/H 12.2 m x 2.4 m x 2.6 m)
- The sensitive nature of cryo-units requires specific transportation methods, e.g. to protect the load from humidity and vibrations.
- The need for high quality requires comprehensive and time-consuming testing of the cryo-units prior to their installation.
- It makes sense to sort cryo-units before they are installed with regard to minor quality differences which also means there is a need for storage areas.

NOTE: *the final quality of cryo-units is influenced by manifold factors affecting production and logistic processes e.g. strong vibrations when handling the cargo. Experience gained from LHC confirms that not all cryo-units will achieve the same quality. Thus, production and logistics concepts should be evaluated regarding the factors which influence the quality. In addition, a sorting area with a capacity for approx. 100 cryo-units is highly recommended to enable minor quality differences in the cryo-units to be compensated for. Buffering and sorting cryo-units makes it possible to identify an optimized installation point for each unit so that the overall quality of FCC is optimized.*

1.2 Supply Chain Design (Structure)

Figure 1-2 shows the main process steps in the production and supply network for FCC cryo-units from the production of components to sorting the cryo-units and transporting them to their installation points. When defining the supply structure, two contrasting production strategies need to be evaluated: (1) is it possible for cryo-units to be completely constructed and tested by CERN (Alternative 1) or (2) is the complete construction and testing of cryo-units by a supplier the preferred alternative (Alternative 5)? A distribution of value adding processes amongst these two different parties is possible and would result in so-called Semi Knocked Down (SKD) production strategies. The diversity of different alternatives is depicted in Figure 1-2. Processes framed in orange are executed by supplier(s), while processes framed in green are executed by CERN. In Alternative 4, the process order varies from the other alternatives presented. Here, the processes for the coldmass test and the assembly of the cryo-unit are reversed. From a technical perspective the process order of Alternative 4 is valid and offers some process advantages e.g. deviation from quality standards (coldmass) can be identified at an early stage and promptly corrected before starting the transport, the transportation of tested coldmass is possible and it is less sensitive than assembled cryo-units.

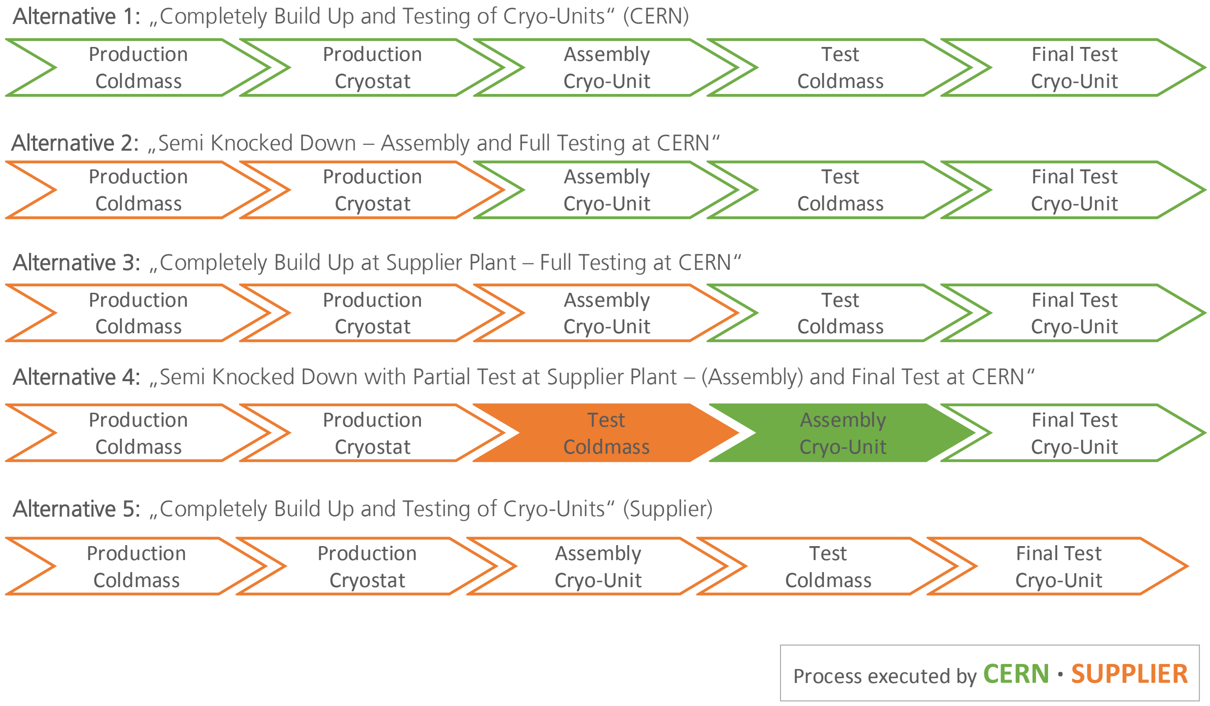

Figure 1-2: Production strategies and distribution of value adding processes between partners

The decision to insource or outsource value added processes (make-or-buy) is a major task when designing the supply chain structure. Which alternative is most suitable for CERN should be evaluated by considering the aspects of ***availability of production infrastructure, transaction costs and product specificity***. Insourcing leads to various ADVANTAGES as CERN has the greatest possible control over production processes and material quality, CERN remains independent of third party suppliers and increases its own know-how of the technology. Finally, purchase and transaction costs can be reduced, the more processes are performed by CERN. The DISADVANTAGE of insourcing is that CERN cannot profit from the technological or process know-how of their suppliers and cost disadvantages due to a lack of economies of scale may arise. All in all, the efficiency of insourcing (Alternative 1) strongly depends on the availability of proper and sufficient production capacities and process know-how. If both aspects are not fulfilled, high costs will arise for building up a suitable infrastructure and/or for modernizing or expanding the existing one as well as for training and recruiting capable employees.

NOTE: As proper infrastructure is currently not available at CERN for producing coldmass or cryostats, outsourcing the cryo-unit production seems to be a valid solution to avoid high infrastructure costs.

With regard to the available resources and considering the fact that the dimensions of the FCC are 4 times higher than those of the LHC (regarding length of tunnel and number of cryo-units), outsourcing processes to suppliers seems to be the favourable solution. Experience gained from LHC production shows that it is possible to outsource the production of cryo-units. For test reasons a small charge of cryo-units was produced and delivered by a supplier. The quality was satisfactory. Outsourcing processes can refer to the entire value-added process (Alternative 5) or only parts of it (Alternative 2-4). Outsourcing is often proposed when suppliers offer the same services or products but at lower cost. Usually the cost reduction is a result of economies of scale or lean production processes.

NOTE: As the final product has neither been designed nor engineered yet, there are currently no suitable suppliers on the market to offer the requested product. As CERN owns process knowledge from producing the LHC and technological knowledge from engineering components for the FCC, collaboration between CERN and the future supplier will be essential. Different levels of supplier integration will be possible here, e.g. financial participation in suppliers by CERN, engineering cooperation, long-term agreements or annual contracts with fixed delivery dates and volumes.

Besides financial aspects, outsourcing – partially or the whole value-added process – entails some risks that need to be considered in-depth in advance.

- **Product Quality:** Outsourcing the processes to suppliers increases the risk of decreased product quality due to the reduced transparency of process execution (production/transport) in the supply chain. The lack of transparency usually rises, the longer the distance between partners is. Poor product quality may result in products being recalled. To prevent these risks, an increase of transparency throughout the supply chain is essential e.g. by investing in quality controls at the suppliers and the manufacturers' plants, as well as participation in the partner selection process. Furthermore, enabling standardized processes while handling the product reduces the risk of incorrect handling processes e.g. using standardized containers for cryo-unit transports will simplify all transport and handling processes as specific transport protection is not necessary.
- **Dependency:** Once the processes are outsourced, a loss of knowledge is to be expected. Once knowledge has migrated, there is a high level of dependency on the supplier. Outsourcing to only one supplier leads to the greatest possible dependency; production shortfalls or bottlenecks in material supply will directly impact supply to FCC that cannot be compensated for.
- **Reliable delivery:** The location of the supplier and the number of stages within the transport network will influence the risk of product damage, shortfalls in production and losses. A production site in politically unstable regions could lead to the risk of strikes, etc. and result in a supply bottleneck. Furthermore, the transport routes are dependent on the production location. Whether unsafe transport routes must be used, or goods must be handled often, e.g. shifted from one means of transport to another, depends on which suppliers are selected. This has a direct influence on process security.

By comparing the advantages and disadvantages of outsourcing, decisions should be made as to whether (gradual) externalization is feasible. Once the outsourcing of processes is decided, suitable partners must be identified. Here, the product can be purchased from a single supplier or from multiple suppliers. *Single sourcing* leads to a high dependency on that one supplier. Nevertheless, compared with *multiple sourcing*, sourcing from one supplier means a reduced logistics network and, therefore, usually leads to decreased logistics costs. In contrast to single sourcing, when using a multi sourcing strategy the product is purchased from several suppliers. This reduces the risk of delivery uncertainty. Whenever a crisis occurs and the production at one supplier fails due to the distributed procurement of magnet volumes, an uncertainty of supply can be avoided. Multi-sourcing results in lower purchase prices due to competition between different suppliers but also usually means an increase in logistics costs resulting from a more widely spread transport network. One major disadvantage of multi-sourcing policy may be a variance in product quality.

Once the decision regarding the number of sources is made, CERN needs to decide on the suitable locations of suppliers (global vs. local). *Global sourcing* enables benefits from reduced production costs resulting from lower labour costs in different countries, but political instability can reverse the positive effect. Nevertheless, on the other hand, fluctuations in exchange rates are common and have a major impact on supply chains serving the global market. To prevent losses, flexible "overcapacities" in the network should be built in to secure the demand from different markets. This flexibility makes it possible to react to exchange rates by changing the production flows in the supply chain but goes hand in hand with a multiple supplier concept.[1] One argument against a global sourcing concept is that it increases the length of transport routes. When shifting the production to other continents transportation by ship is the most common means of transport. However, the sensitivity of cryo-units demands an increased effort to protect the goods being transported against vibration/shocks or humidity, etc. *Local sourcing* results in decreased transport distances and thus lower logistics costs. The shorter the distances between the partners, the stronger the customer-specific production can be, and it also leads to decreasing transaction costs. Eliminating all the risks of global sourcing may not balance out the labour cost savings that are gained by producing in other countries.

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[1] Chopra – Supply Chain Management 2010, Page 126ff.

2 Location of and transport to CERN sites

2.1 Possible locations based on transport requirements

2.1.1 General approach

First, the overall aim of applied research in logistics is to develop robust logistics strategies. To achieve this goal, it is necessary to fulfil several tasks. In addition to the analysis of the current network structure and its weak points, it is necessary to forecast the logistics dimensions for the future.

Furthermore, it is important to take different goals into account. In the first place, minimized costs are requested. Apart from that, the service quality and the general network structure have to be improved and total costs have to be calculated according to current cost figures and prices. In addition, neutral recommendations are needed, which are based on certain criteria relevant for decision-making.

During the process of a typical project a few steps have to be considered: a discussion of future requirements and expected developments to define the targets is followed by a model of current structure and transport volumes as a baseline. Then bottlenecks, weak points and possible quick wins have to be identified. In the next step the optimization of the whole process is paramount. To this end, the different optimization variants should be fully discussed before deploying the IML-tool DISMOD®. Finally, a discussion and comparison of results with respect to costs, service level and robustness in relation to necessary structural changes is essential before the rollout.

At this point, the advantages of DISMOD®, a modular tool used for planning logistics networks, should be mentioned. DISMOD® is an inhouse tool for analysis and optimization with high adaptability levels due to its modular design and modern and flexible optimization methods. It includes an embedded Geographical Information System (GIS) with a display of ZIP-code regions, EURO NUTS or administrative districts. The visualisation of logistics networks and structures and distribution and procurement logistics are just two domains in which the DISMOD® tool can be useful. Moreover, it can be utilized for route planning, for warehouse simulation or to find out the benchmark for freight costs.

2.1.2 Approach: DISMOD® planning for FCC

There are three main steps while using the DISMOD® tool: first of all, the coordinates of FCC and the shafts have to be uploaded into DISMOD®, visualizing the current planning for FCC. After that, one has to identify possible site candidates for assembly, testing and logistics. The next step is to agree on structure variants to be analysed in detail and then optimize logistics networks by using DISMOD®. Finally, the results should be analysed and compared to determine the logistics structure for FCC.

2.1.3 Requirements

In accordance with the experience gathered from other location and site planning projects, the sites for assembling, testing and storing magnets and cryo-units should meet certain criteria. At this stage of the analysis, the detailed processes and their extent has not been determined yet. However, the following criteria seem meaningful for further analysis:

- suitable size: approx. 10 ha (100,000 sqm)
- convenient access to major roads
- not in: city centres, mountain areas, nature reserve, e.g. Lake Geneva
- near to sufficient power supply

The DISMOD® gives an overview of the site candidates from section A-B to A-L and the middle. The longitude and latitude and the name of the country and city of the location is given. It also analyses the different types of areas and additional information about the locations, like asphalted ground or a highway.

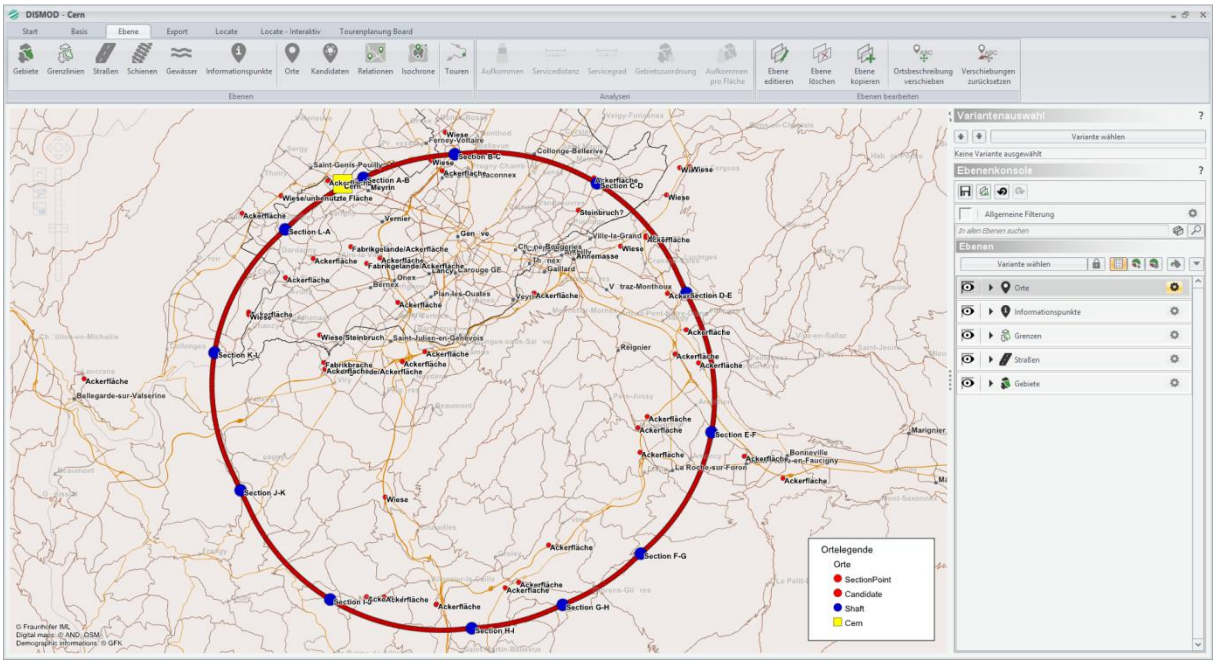


Figure 2-1: DISMOD® tool visualizes possible areas

PID	Section	Usage	City	xLongitude	yLatitude	Acces to Motorway?	Electricity?	Info
1	Center	Field (Agriculture)	Neydens, Frankreich	6.09502	46.13104	1	1	Motorway Exit
2	Center	Industrial / Agriculture	Viry, Frankreich	6.03218	46.12665	1		Railway Connection
3	Center	Field (Agriculture)	Saint-Julien-en-Genevois, Frankreich	6.1133	46.1369	1		Motorway Exit
4	A-B	Meadow (Agriculture)	Ferney-Voltaire, Frankreich	6.118145	46.247884	1		near Airport
5	A-B	Industrial / Agriculture	Satigny, Schweiz	6.05310	46.19771	1		
6	A-B	Field (Agriculture)	Russin, Schweiz	6.02251	46.19081		1	
7	B-C	Meadow (Agriculture)	Bellevue, Schweiz	6.1298	46.2640	1		near Airport
8	B-C	Field (Agriculture)	Le Grand-Saconnex, Schweiz	6.127343	46.241713	1		near Airport
9	B-C	Field (Agriculture)	Meinier, Schweiz	6.250528	46.237587		1	near Railway
10	B-C	Quarry?	Choulex	6.23798	46.21893			
11	C-D	Meadow (Agriculture)	Cranves-Sales	6.2930	46.2040	1		
12	C-D	Meadow (Agriculture)	Annemasse/Ville-la-Grand, Frankreich	6.272292	46.197983			near Airport
13	C-D	Field (Agriculture)	Cranves-Sales	6.292760	46.203089	1		
14	C-D	Meadow (Agriculture)	Machilly, Frankreich	6.32026	46.24347	1		near Industrial Area
15	C-D	Meadow (Agriculture)	Machilly, Frankreich	6.3287	46.2439	1		near Airport
16	C-D	Meadow (Agriculture)	Saint-Cergues	6.3097	46.2277	1		
17	C-D	Field (Agriculture)	Bonne, Frankreich	6.310359	46.170533			
18	C-D	Field (Agriculture)	Etrembières, Frankreich	6.2020	46.1708	1		near Quarry
19	D-E	Field (Agriculture)	Contamine-sur-Arve	6.33558	46.13032	1		near Industrial Area
20	D-E	Field (Agriculture)	Fillinges, Frankreich	6.325555	46.149541	1		
21	D-E	Field (Agriculture)	Scientrier, Frankreich	6.316465	46.135511	1		
22	D-E	Field (Agriculture)	Cornier, Frankreich	6.293932	46.099232	1		
23	E-F	Field (Agriculture)	Bonneville, Frankreich	6.4042	46.06335	1		near Industrial Area
24	E-F	Field (Agriculture)	Bonneville, Frankreich	6.37277	46.07618	1		near Industrial Area
25	E-F	Field (Agriculture)	Etaux, Frankreich	6.288057	46.078444			
26	E-F	Field (Agriculture)	Cornier, Frankreich	6.286568	46.092734	1		
27	F-G	Field (Agriculture)	Evires, Frankreich	6.213847	46.024606	1		
28	G-H	Field (Agriculture)	Groisy, Frankreich	6.189446	46.002959	1		
29	G-H	Field (Agriculture)	Groisy, Frankreich	6.178539	45.999790			
30	H-I	Field (Agriculture)	Villy-le-Pelloux, Frankreich	6.122415	45.990064	1		
31	H-I	Field (Agriculture)	Choisy, Frankreich	6.065819	45.994627			
32	H-I	Field (Agriculture)	Allonzier-la-Caille	6.122795	45.990271			
33	H-I	Field (Agriculture)	Allonzier-la-Caille	6.080375	45.994362			
34	H-I	Meadow (Agriculture)	Copponex, Frankreich	6.08102	46.05250	1		asphalted Area
35	J-K	Field (Agriculture)	Lancrans, Frankfurt	5.836420	46.121095			
36	J-K	Field (Agriculture)	Viry, Frankreich	6.03218	46.12696	1		near Industrial Area
37	J-K	Industrial / Fallow	Viry, Frankreich	6.03125	46.13054	1		near Industrial Area
38	K-L	Field (Agriculture)	Saint-Jean-de-Gonville	5.964598	46.217013	1		
39	K-L	Field (Agriculture)	Challex, Frankreich	5.970139	46.159779		1	
40	K-L	Field (Agriculture)	Bernex, Schweiz	6.07671	46.19115	1		Motorway Exit
41	K-L	Meadow / Quarry	Avusy, Schweiz	6.02776	46.14651			
42	K-L	Meadow (Agriculture)	Challex, Frankreich	5.97007	46.15830		1	
43	K-L	Field (Agriculture)	Dardagny, Schweiz	5.99999	46.17978			near Railway
44	L-A	Field (Agriculture)	Saint-Genis-Pouilly	6.0343	46.2360		1	
45	L-A	Meadow (Agriculture)	Thoiry, Frankreich	5.99643	46.22724			
46	L-A	Field (Agriculture)	Confignon, Schweiz	6.0913	46.1654	1		Motorway Exit
47	L-A	Industrial / Agriculture	Bernex, Schweiz	6.06600	46.18795	1		

Figure 2-2: DISMOD® chart shows exact data of possible site candidates

The process for identifying the candidates consisted of surveying the area along the planned tunnel, inside the tunnel and partly outside the ring. Plots of land were analysed according to their size and to their current usage. Connections to the road network were analysed as well as connections to the electricity network (if possible). However, the ownership / availability of the plots of land was not checked at this stage of the survey.

In the following map one example location is displayed: Neydens, France (46.13104 N 6.09502 E).

Figure 2-3: Map of France on the border to Switzerland; example location near a motorway exit

2.1.4 Conclusion

A study analysing the availability of plots of land for building larger infrastructures for assembling and testing etc. cryo-units near the defined locations of shafts has already been carried out for the shafts on Swiss territory and is ongoing for shafts on French territory.

The result for shafts on Swiss territory is that only at point A (close to the CERN campus) is sufficient land possibly available in the direct vicinity of the shaft. Since the area near point A is also very favourable due to its proximity to the CERN campus, this location is a good choice for an assembly and testing facility for cryo-units. This plot of land is available for CERN and reduces the need for surface transportation of fully constructed cryo-units to a minimum. Also, the collaboration between the CERN campus and the assembly and testing facility is simplified because of the close proximity.

The second shaft for cryo-unit transport should be located at point E – nearly opposite point A and which makes it an optimal backup for shaft A. The overall depth of shaft E is the lowest of all shafts and so shaft E will be cheaper to construct than the shaft at point F for example.

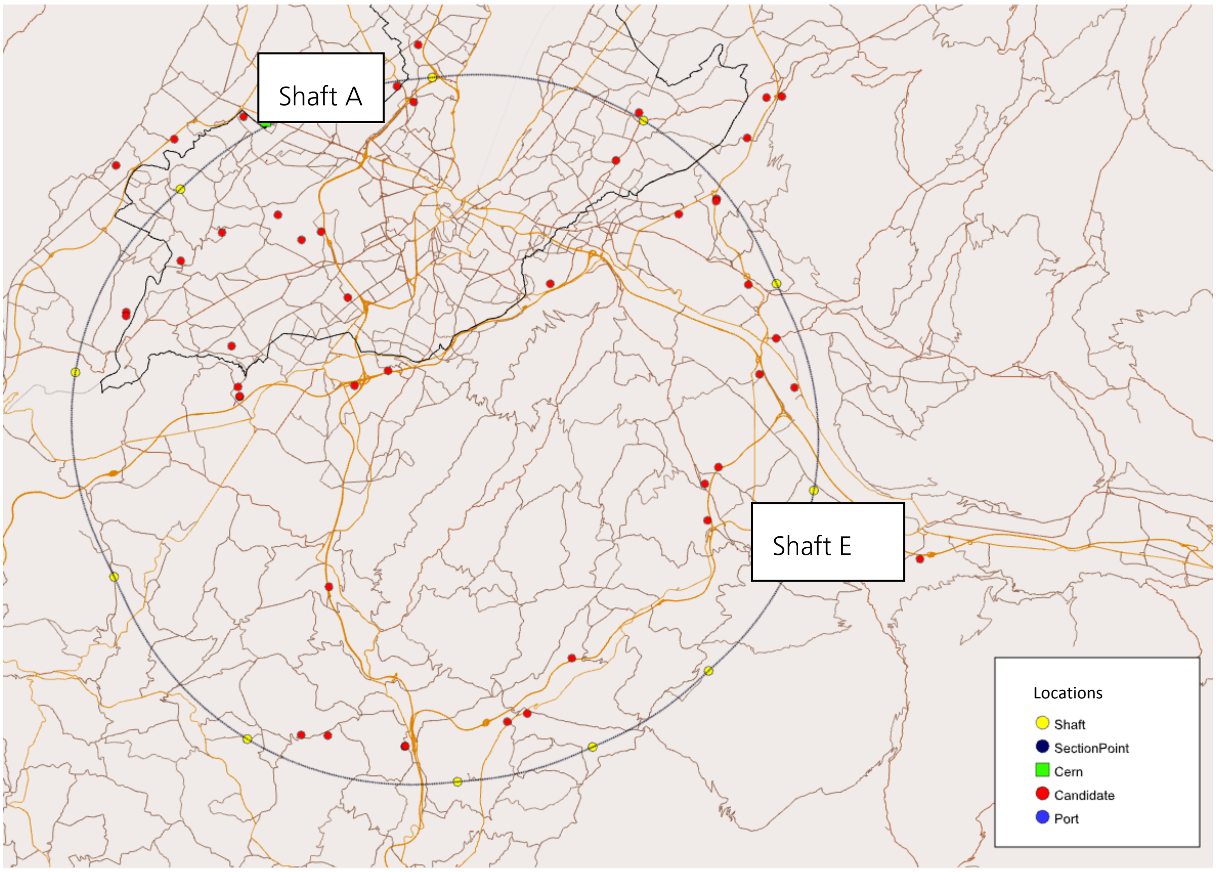


Figure 2-4: CERN Campus, Shafts A and E

If the available area at point A is large enough for assembling and testing facilities for all required cryo-units, one large single facility should be built at point A in order to use economies of scale and higher utilization rates of equipment and possibly personnel during the assembly and testing of cryo-units.

If the space at point A is not sufficient for one large facility, the second facility should be located at point E. If the transportation of cryo-units between point A and E is necessary, this should – if possible during the installation phase – be undertaken in the tunnel. If transportation inside the tunnel is not possible, then transportation should take place on the surface.

The overall space needed for the assembly and testing facilities depends on the supply chain strategy that is chosen. If many processes take place at these facilities, large areas are needed. If few processes take place at these facilities, a smaller space is needed. The different strategies are discussed in detail in chapter 4. However, it is not part of this report to perform detailed layout planning of assembly and testing facilities. For the current analysis it is assumed that the area near point A is sufficient to incorporate the assembly and testing facilities.

2.2 Transport chain design for cryo-units and equipment

To ensure successful transportation DISMOD® provides assistance with the exact route planning. Firstly, every possible route was listed. In the next step the stops for the selected route were registered, followed by an appropriate sequence of the selected stops.

Considering the difficulties involved in transporting cryo-units, various production strategies are needed to design and assess scenarios for cryo-unit and detector installation. The pros and cons of FBU and SKD have to be evaluated in this context. Furthermore, it has to be decided if the process should be central or decentral. To handle the long-distance supply of CERN locations by plane, barge, rail or truck, the potential transport modes and volumes depending on their sources and SKD/FBU have to be assessed. Potential transhipment equipment and transhipment points and their recommendation must be included as well. In addition, it is important to consider that the needs of packaging depend on the capability of SKD and FBU for transportation.

However, the regional supply of CERN locations involves a few special characteristics: the potential transport modes and volumes have to be evaluated too, but the needs for space at the different access and assembly sites must also be identified. Moreover, conditions and bottlenecks in local transport networks are taken into account to bypass the difficulties.

Keeping in mind all these requirements, certain information will be necessary before it is possible to imlement the transportation of cryo-units. First of all, you need to know the GIS data of the planned CERN tunnel, the volumes of cryo-units, detectors, sensitivities and frames for handling cryo-units and the detectors FBU and SKD including the differentiation of the SKD parts. In addition, it is essential to get more detailed information on quadrupole and special magnets (and their transport chains) delivered from the US to CERN during the LHC project. The traffic volumes in the public transport infrastructure is just as pertinent as the requirements for different types of locations with regard to transporting people, cryo-units or detectors. The same applies to the final construction and testing, too. Furthermore, the GIS data of the electric network, its capacities and capacity utilization need to be estimated if the electricity network needs to be extended.

In the basic scenario the focus is on the process planning times for e.g. cryo-unit tests, assembly or installations. The planning assumptions should be determined regarding four aspects: at first, the network structure should be taken into account. That includes production facilities, requirements for transport capacities especially at the harbour, available assembly hall capacities or required capacities for assembly and testing. Secondly, the processes should be described to clarify which strategies are preferred, if FBU is possible, if the cryo-unit testing can be outsourced and if all needed resources are available. The third aspect, called ‘planning assumptions’ in general, contains the order lead times, which have to be considered as well. The last aspect points to the cryo-unit as a product and its degree of segmentation of cryo-units (SKD).

2.3 Impacts on goods during transport and transhipment

Long distance or even intercontinental transport will expose the cryo-units to certain transport stresses. This depends on the chosen mode of transport and on the transport distance and therefore the transport time.

The following major transport stresses have been identified:

- Shocks
- Vibrations
- Temperature
- Humidity
- Sea water
- Air pressure variances
- Others

Of all the transport stresses, shocks are the most relevant transport stresses for the cryo-units. The design of the LHC cryo-units prohibits shocks of more than 0.1 g. However, in the past, some FCC cryo-units have been equipped with removable transport restraints in order to increase the shock tolerance of the units.

For the FCC it could be meaningful to find a cryo-unit design that is tolerant to shocks (much) higher than 0.1 g or alternatively to design specific transport restraints that increase the g shock tolerance during transport and handling.

Different modes of transports have different expected transport stresses. In general, the following possibilities for long distance transport exist:

- Road transport
- Rail transport
- Air transport

- Inland waterway transport (barge)
- Sea-going vessel

Each mode of transport has specific characteristics, limitations, advantages and disadvantages.

Road transport

Figure 2-5: Transport stress (g shocks) expected for road transport

Road transport is a comparatively cheap mode of transport with the possibility of last mile and door-to-door transport. However, road transport is not ideal for intercontinental transportation and of course, it cannot cross oceans etc. When it comes to large and heavy loads, road transport is somewhat limited: if the weight of the load exceeds approx. 25 t, special equipment is needed and planning transportation gets much more complex and expensive. The transport stresses to be expected during road transport are in the magnitude of 1 g.

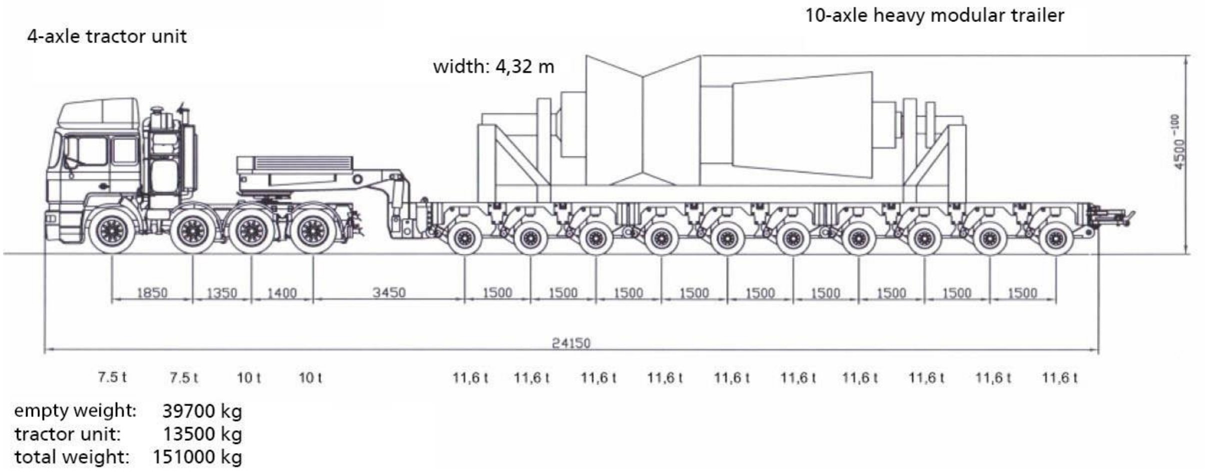


Figure 2-6: Example truck and trailer configuration for heavy load

Rail transport

The second alternative is rail transport. Rail transport is also relatively cheap. It is a very safe mode of transport concerning accidents but in general, rail transport is not as flexible as road transport. Costs for heavy loads are on the same level as road transport. The transport stresses in general are within the same range as road transportation but there can be critical peaks especially during shunting, decoupling and depending on the quality of the tracks.

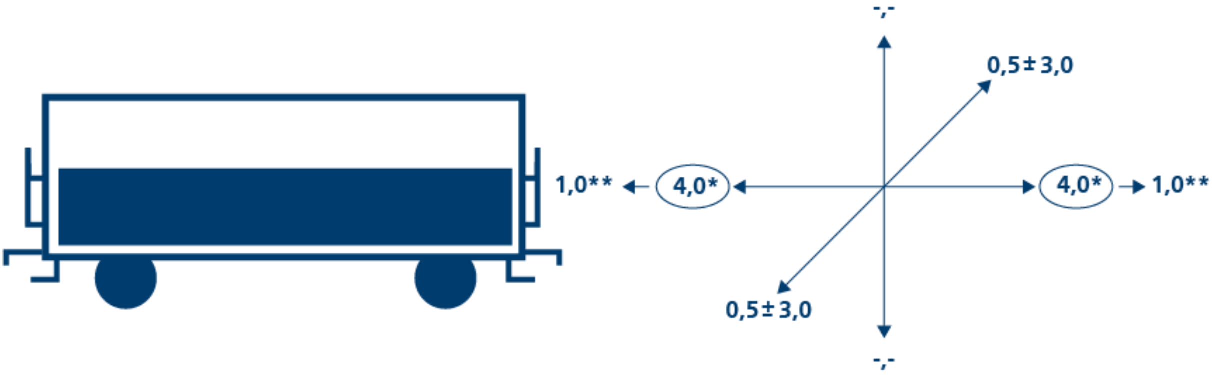


Figure 2-7: Transport stress (g shocks) expected for rail transport

Inland waterway (barge)

The transport stresses are comparable to the transport stresses during road transport. The flexibility is lower than with road transport. Transport prices are comparable.

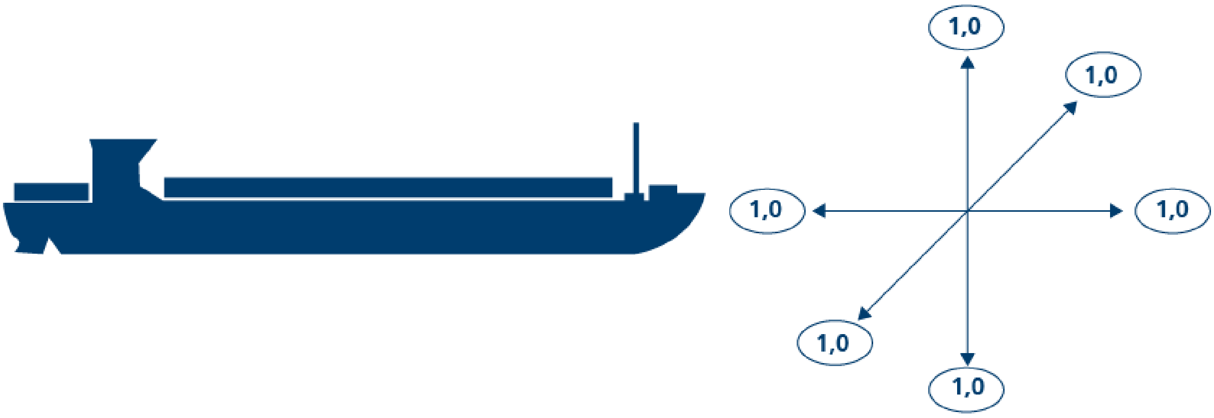


Figure 2-8: Transport stress (g shocks) expected for barge transport

In general, inland waterway transportation is very suitable for heavy goods transport. For transporting cryo-units, the weights and dimensions are not problematic. However, CERN cannot be reached by inland waterway directly. Suitable terminals for inland waterway transport are either Basel in Switzerland or Mâcon in France. The remaining transportation from Basel or Mâcon to CERN has to be performed by road transport.

Air transport

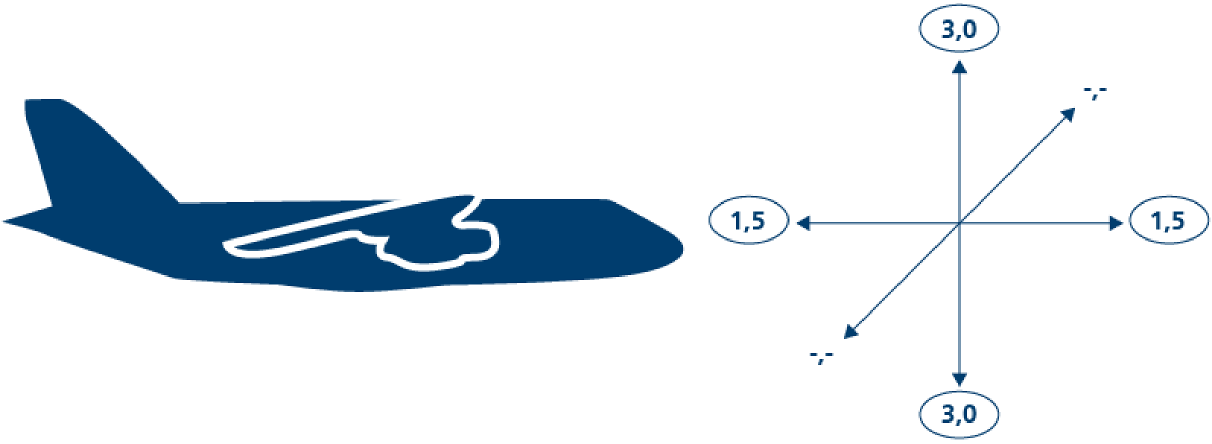


Figure 2-9: Transport stress (g shocks) expected for air transport

Air transport is very fast but during take-off and landing, very high transport stresses can occur. As a result, air transport does not seem to be suited to the standard long distance transportation of large numbers of cryo-units. However, it might be possible to use air transport in situations where single or just a few cryo-units have to be transported over a long distance in a short time. It is necessary to analyse whether the aircraft (e.g. Antonow An-124) can land at Geneva airport or at which other nearby airport.

Sea transport

After excluding air transport due to high transport stresses, sea transport is the only possible means of transport capable of crossing oceans and thus making international transport possible.

For sea transport, there are four principal alternatives:

- Containerized transport
- RoRo transport (roll-on, roll-off)
- General cargo
- Project freight with special vessels

Containerized transport is the standard way to transport (non-bulk) freight, however maximum weights and sizes have to be taken into account. 53’ containers can transport items up to 16 meters long and 25 t as a standard configuration. Flat rack containers can be utilized with payloads of up to 50 t – however at higher transport costs.

If the cryo-units design is in line with standard container sizes, this would lead to comparatively low transport costs for overseas transport.

RoRo is the second possibility. Specialized RoRo vessels are needed. The availability of passages etc. is limited compared to containerized transport. Costs will be moderately higher than for containerized transport. Depending on the source and destination, RoRo transport is a possible alternative.

For general cargo the weights and sizes of the cryo-units are expected to exceed the maximum dimensions possible (at moderate transport costs). This alternative therefore seems to be the least favourable.

The fourth possibility is project freight. Special vessels – often with heavy load lifting equipment on board – can transport heavy and bulky (project) freight. This can be a very interesting alternative to containerized transport since the maximum dimensions and weights are not as limited as with containerized transport. Due to the length of the installation phase it might be possible to charter vessels and operate them in a kind of shuttle transport A – B – A. Maybe it could even be possible to combine other heavy loads (e.g. wind turbines) on the otherwise empty way back to the producer of the cryo-units. This approach needs further investigation which should be carried out once possible locations of overseas producers of cryo-units are identified since the resulting transport costs etc. heavily depend on the sources and destinations of the transports.

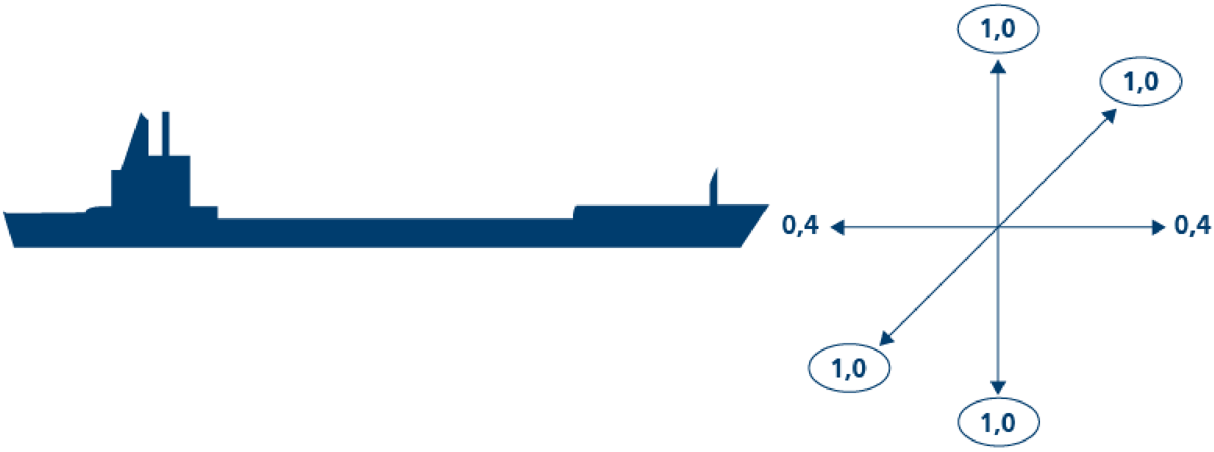


Figure 2-10: Transport stress (g shocks) expected for sea transport

Comparison of transport alternatives

	Transport Stress	Cost	Flexibility	Speed	Complexity of Organization
Road	+	+	++	+	+
Rail	o	+	O	O	O
Barge	+	+	o	O	+
Air	-	--	+	++	+
Seagoing ship	+	+	+	O	+

Figure 2-11: Comparison of transport alternatives

As a result of the comparison of transport alternatives, none of these standard transport modes can be used if the cryo-units can only accept shocks of max. 0.1 g. In this case, specialized road transport is the only solution. However, such specialized road transport does not make sense for long distances (> 100 km).

If it is possible to find a cryo-unit design that can accept shocks of up to 1 g (or if it is possible to install comparable transport restraints during transport and handling), transportation of cryo-units over longer distances is possible for road transport, for barge transport and for sea transport.

Conclusion

The transport chain from an overseas producer of cryo-units could be designed as follows:

1. Truck transport to sea port
2. Sea ship transport to either a) Rotterdam or b) Marseilles
3. Truck transport from sea port to CERN (alternatively: barge transport from a) Rotterdam to Basel / b) Marseilles to Mâcon and then via truck to CERN

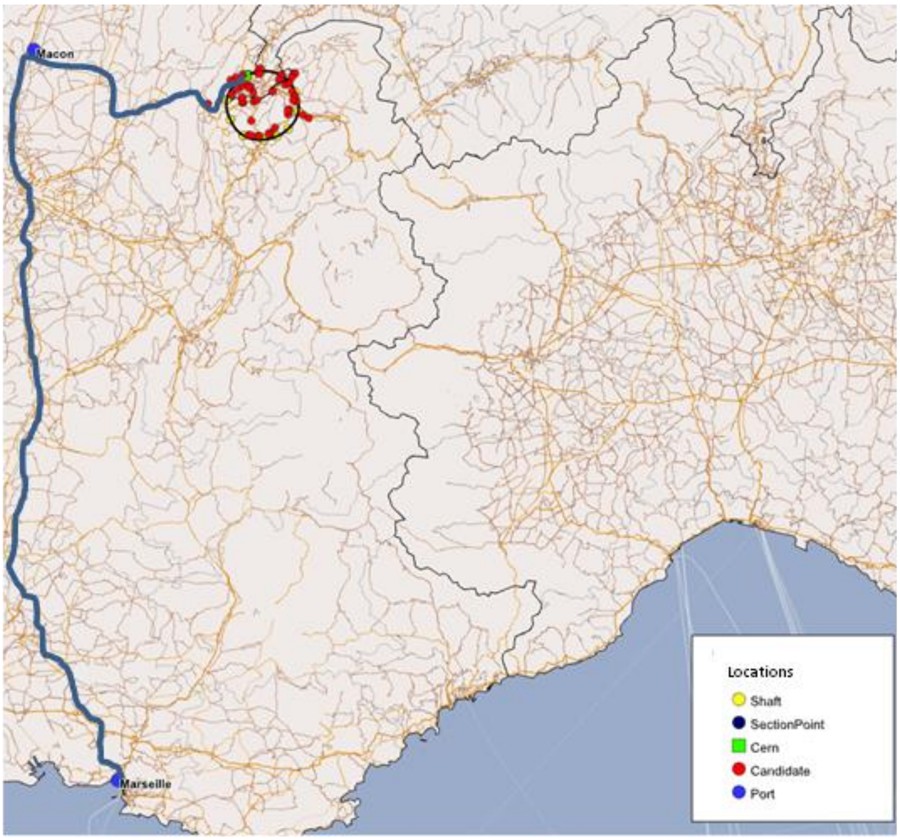


Figure 2-12: Route Marseilles, Mâcon, CERN

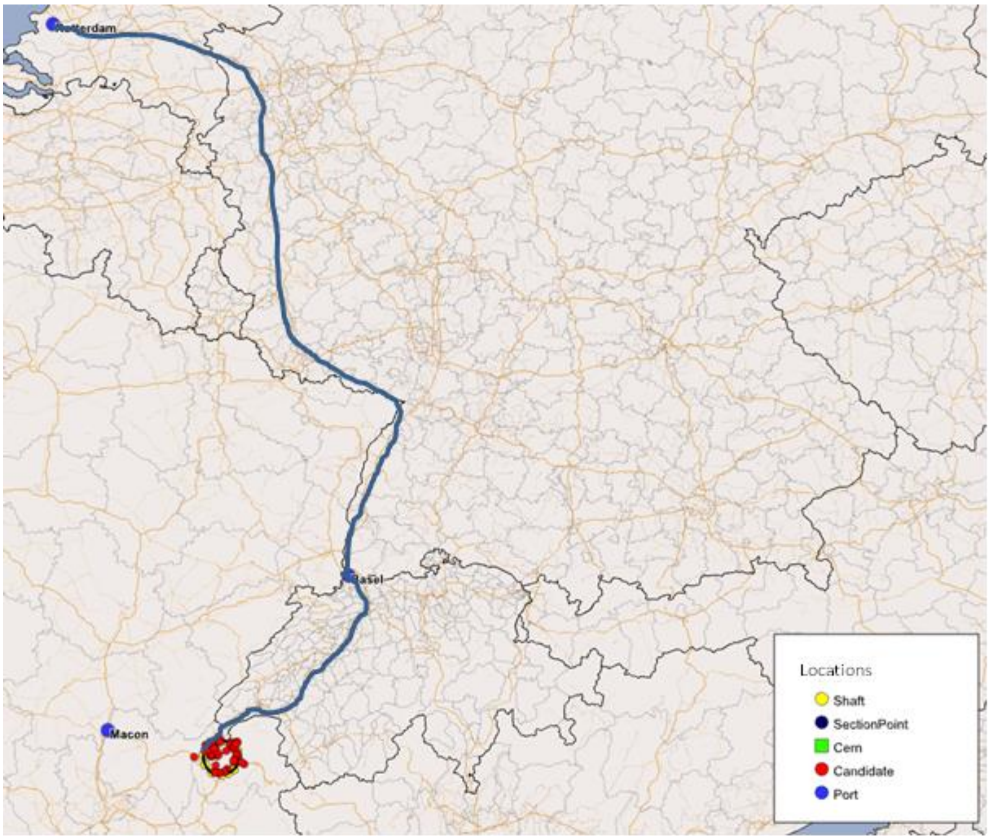


Figure 2-13: Route Rotterdam, Basel, CERN

2.3.1 Estimation of costs for heavy weight transport with max 0.1g shocks.

Concerning the costs for heavy weight transport with max 0.1 g shocks the costs can be assumed to be in an order of magnitude of 10 higher than the transport costs for “normal” heavy weight transport.

A first price indication shows ca. 15,000 Euro for long distance sea transport, 5,000 Euro for inland truck transport and 20,000 Euro for insurance costs.

A prediction of the future development of prices for such special transports is difficult, experiences from the past have shown that prices for standardized transport services grow significantly slower than prices for transport with special (and rarely demanded) requirements. Hence it can be assumed that the difference between transport prices for cryo-units with normal g shock requirements and transport prices for cryo-units with extra low maximal g shocks will increase further in the future.

3 Underground transport and handling of cryo-units

The scenarios described in the previous chapters for the delivery and verified delivery of the FCC cryo-units to the construction site are now supplemented by the concept of underground transport within the FCC. The focus is on both transporting cryo-units directly to the installation site by underground transport and the handling of cryo-units in the FCC tunnel. To this end, suitable principles for the transport and handling of the cryo-units in the tunnel will be elaborated and evaluated.

The following tasks for underground transport and handling (via transfer tables) were identified:

- Elaboration and evaluation of suitable principles for underground transport
- Elaboration and evaluation of suitable principles for handling the cryo-units
- Development of design proposals for the transport vehicle
- Development of design proposals for the handling equipment (transfer table)
- Search for technology suppliers (if possible: involving industrial partners)
- Development of a safety concept

All in terms of:

- Heavy transport under cramped conditions (in tunnels)
- Steering
- Navigation
- Power supply of the active components
- Safety (collision avoidance, personal protection)
- Performance (throughput)

3.1 Systematic approach

Selection of possible technologies and characteristics in subsequent topics:

3.1.1 Overview of the execution of the track

The following image shows the basic principles for different surfaces, but a concrete surface is considered advantageous for the route.

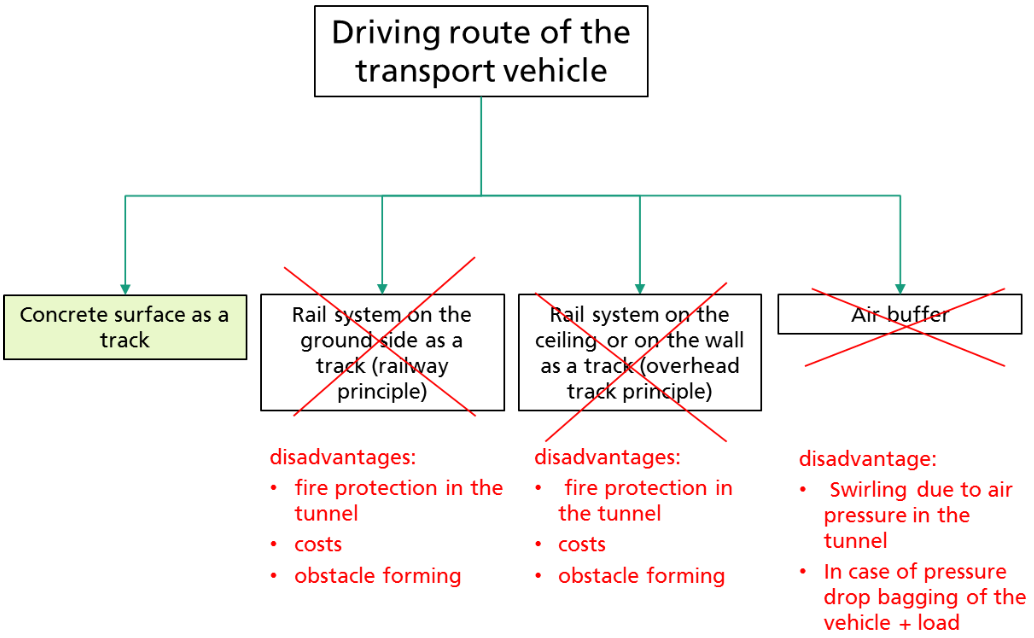


Figure 3-1: Basic principles for different surfaces

3.1.2 Overview of the power supply

An exhaust-free electric drive (power unit) is recommended as the power supply for the vehicles.

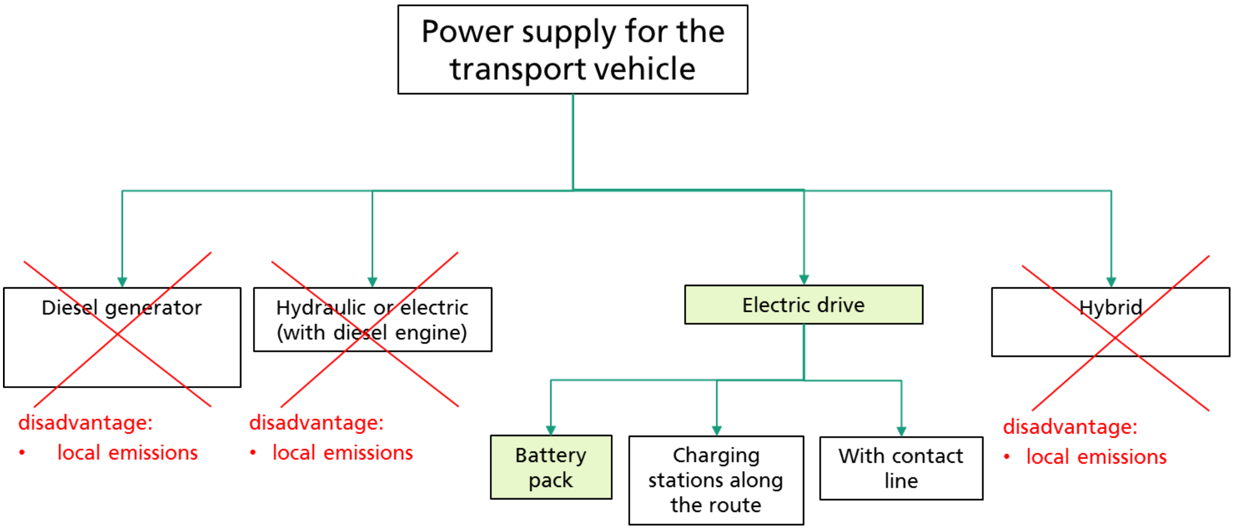


Figure 3-2: Basic principles for power supply of the vehicles

3.1.3 Overview of the steering / navigation

The control and navigation system can be implemented from both ends which is expedient.

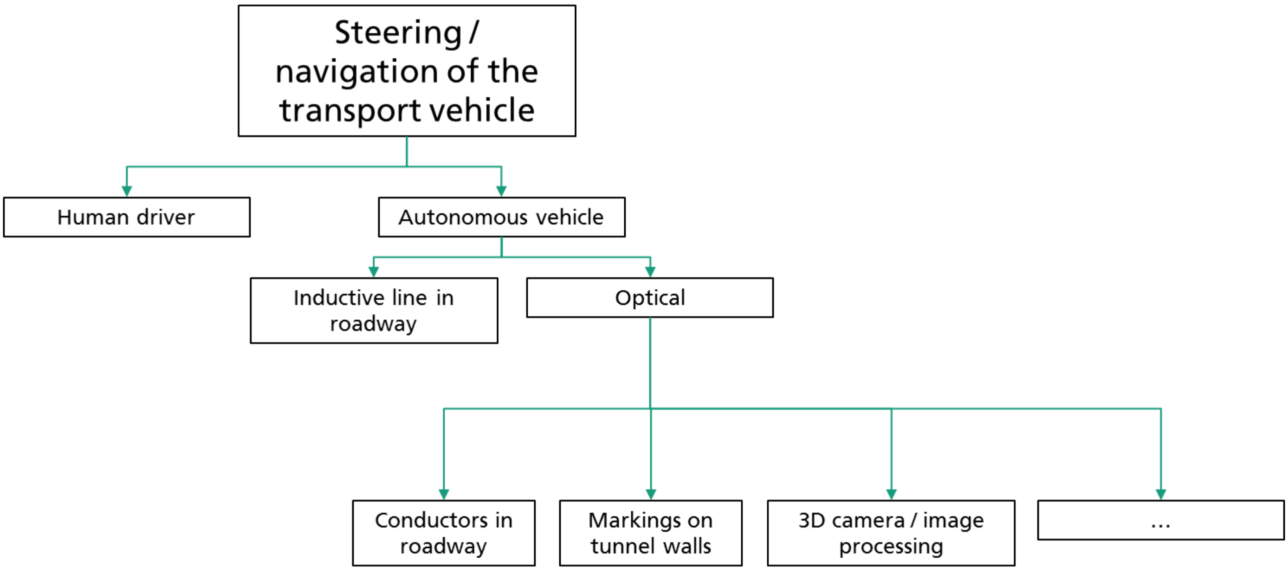
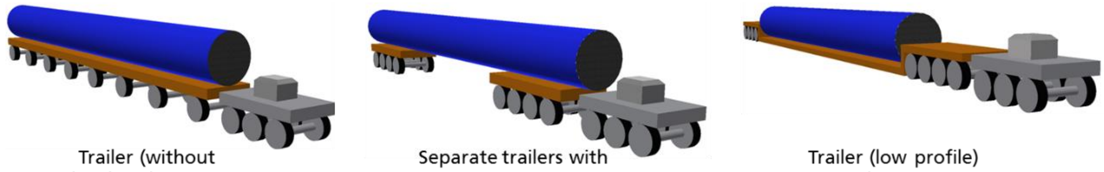


Figure 3-3: Basic principles for steering and navigation of the vehicles

3.2 Vehicle concept

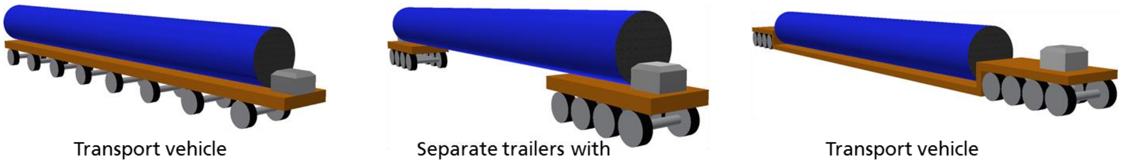
The possible basic principle of transportation is listed as shown below in order to determine a preferred variant for the subsequent work.



Trailer (without drive) with tractor

Separate trailers with tractor

Trailer (low profile) with tractor



Transport vehicle with its own drive

Separate trailers with drive and support

Transport vehicle (low profile) with its own drive

Figure 3-4: Basic principle of transportation

3.2.1 Optimal transport concept: separate trailers with tractor

The separate trailers are preferred because they have the most favourable features when deployed in the tunnel. These trailers are the most adaptable with regard to the cargo being transported (the length of the cargo is not relevant due to there being separate carriages).

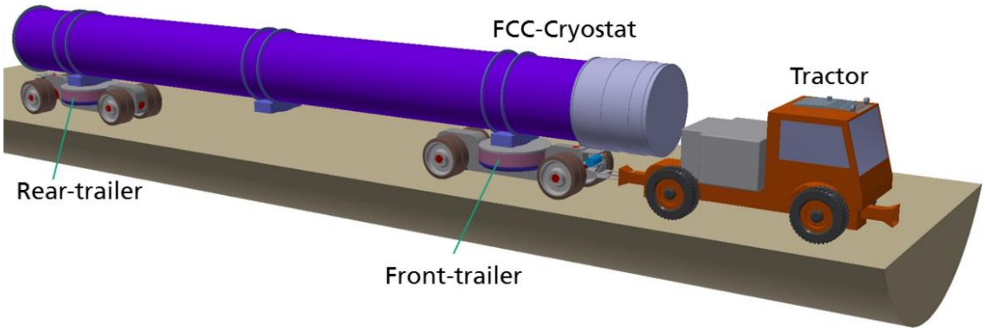


Figure 3-5: Overview of the elements during transportation of the FCC-cryo-units in the tunnel, here shown with a tractor and two trailers.

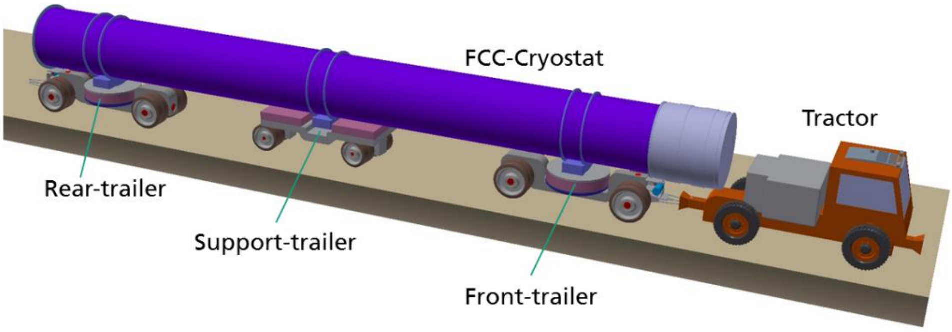


Figure 3-6: Diagram showing a supporting third trailer (Support-trailer) if support for the centre of the FCC-cryo-units is required during transportation in the tunnel

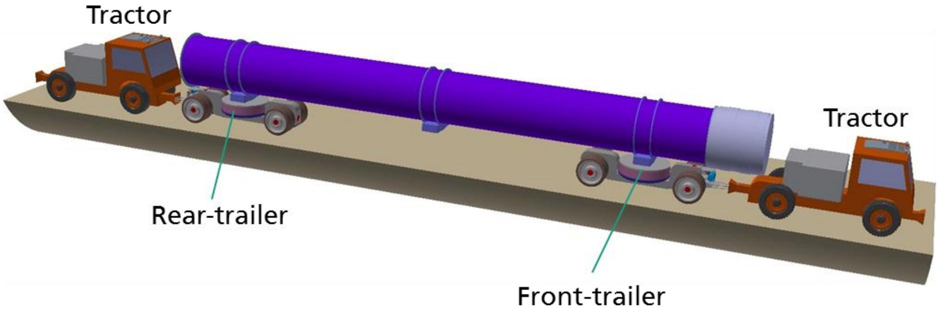


Figure 3-7: One or more tractors can be used for driving in the same direction, depending on the transport strategy

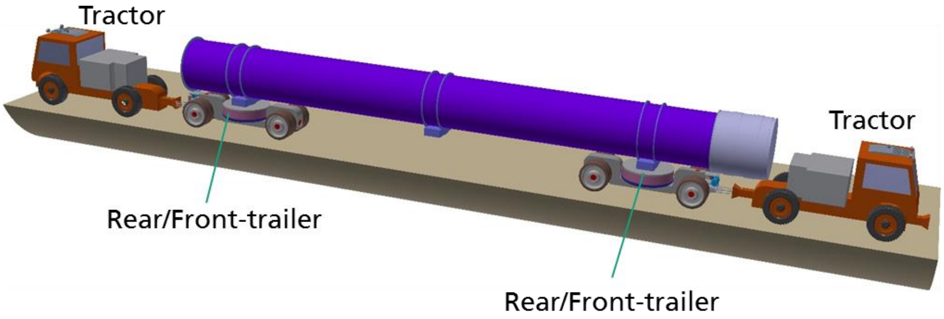


Figure 3-8: Figure 3 7: One or more tractors can be used for driving in opposite directions, depending on the transport strategy

The different direction of the tractors during transport can be selected according to the approach strategy and the empty-drive strategy. The illustrated constellation supports the fast and empty (unloaded trailers) journey back to the loading point at the shaft.

3.2.2 Detailed trailer concept

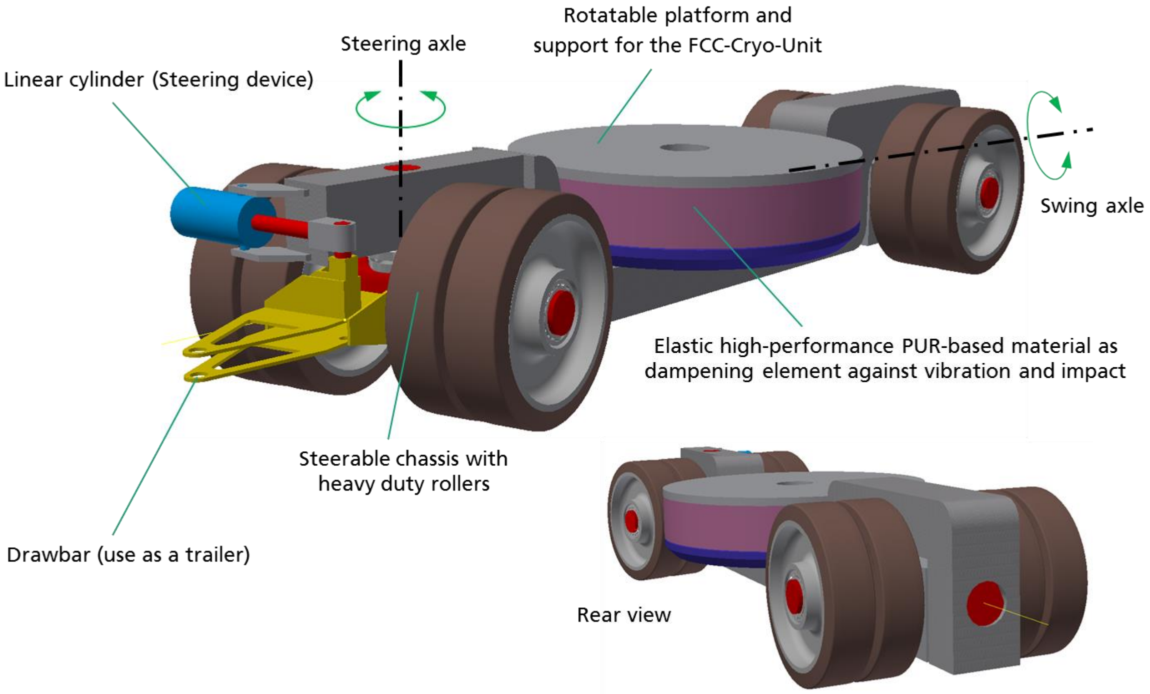


Figure 3-9: Detailed solutions demonstrating certain functions of the trailer

The transport trailer provides an electronic steering system, a drawbar and a vibration-dampening support for loading. Ground contact for the special wheels is maintained by using pendulum axles (swing axles).

3.2.3 Support trailer

Because of its two steering axles the support trailer is capable of carrying out any steering movement for the FCC cryo-units during transport. The FCC cryo-unit is securely located on vibration- dampening beds during transport.

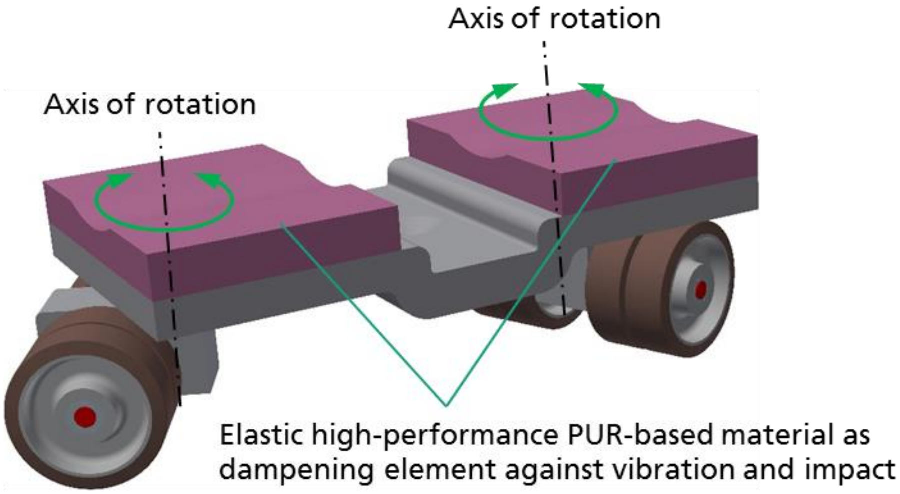


Figure 3-10: The support trailer is used if support is required for the centre of the FCC cryo-unit during transport

3.2.4 Tractor

The tractor is equipped with two trailer hitches (in both the front and the rear). The towing hitches connect the tractor to the trailers and are used when the trailers are loaded and unloaded.

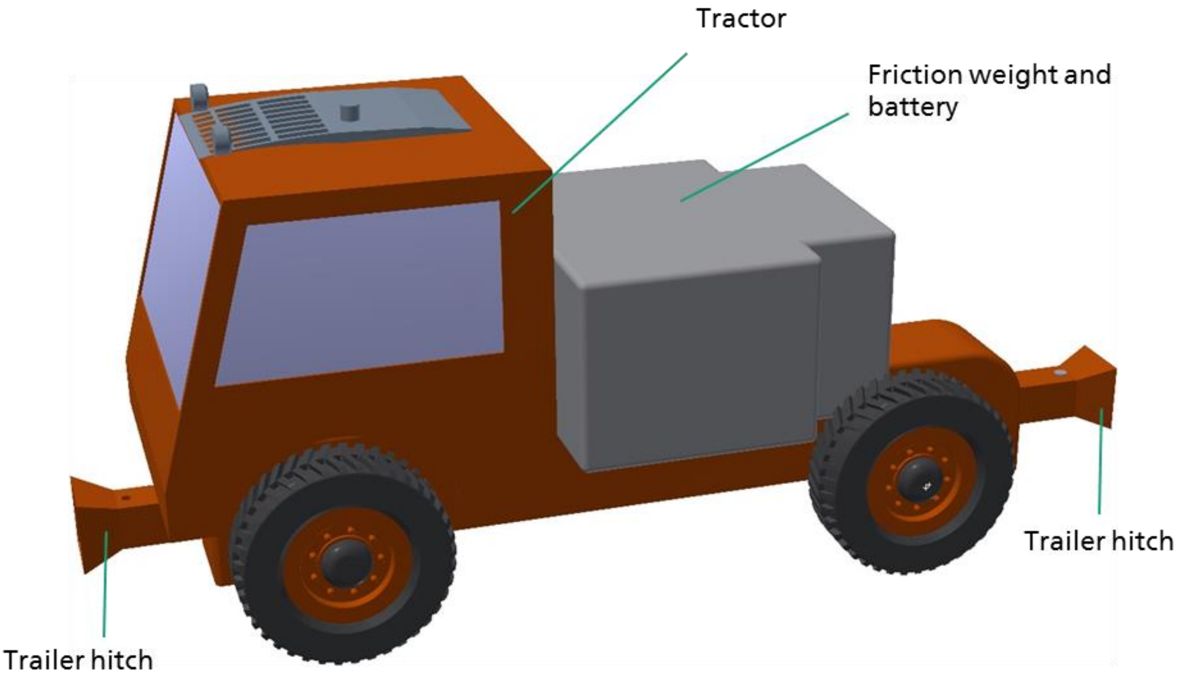


Figure 3-11: Visualisation of tractor

The tractor is equipped with electric, emission-free drive. An intelligent navigation and control system enables automated driving in tunnels.

3.3 Handling concept for cryo-units in the tunnel

The handling concept describes the transhipment of the load from the transport vehicle to the assembling position of the FCC cryo-unit in the tunnel.

Two transfer tables equipped with hoists are used for unloading the cryo-units from the transport vehicle.

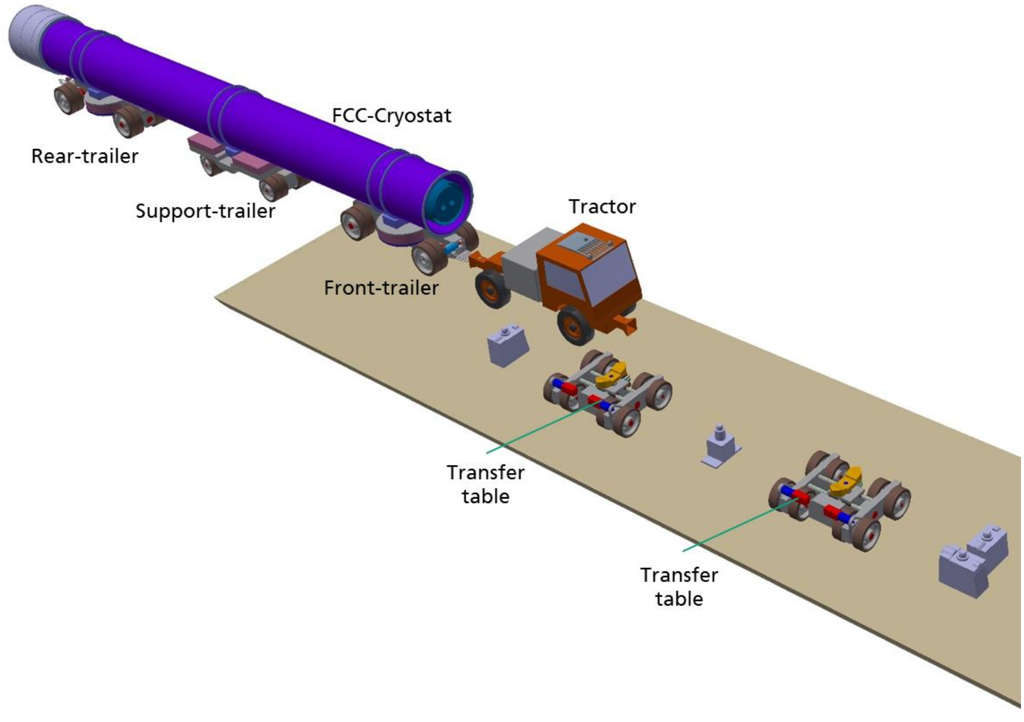


Figure 3-12: Visualisation (1) showing use of transfer tables

The tractor transports the FCC-cryo-unit to the designated assembly point in the tunnel. There, two transfer tables trans-ship the FCC cryo-unit from the trailers onto the mounting position.

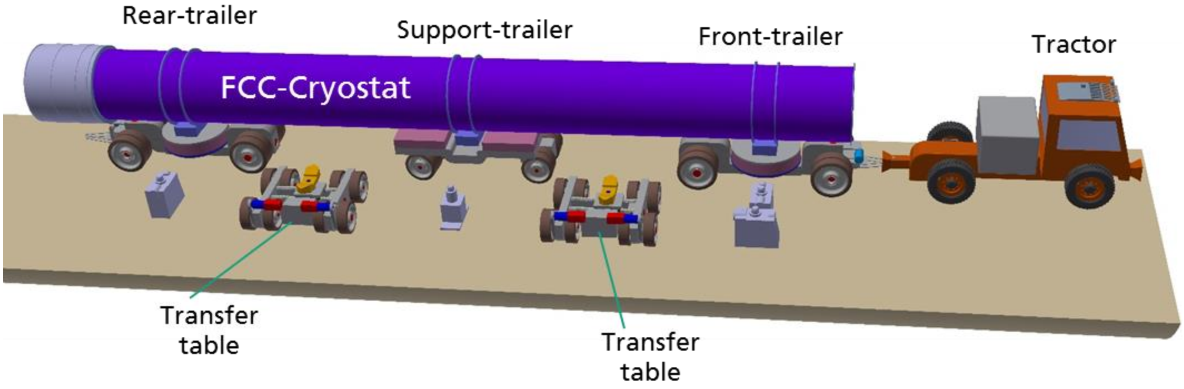


Figure 3-13: Visualisation (2) showing use of transfer tables

When the tractor with the FCC-cryo-unit arrives at its designated position (mounting position for the next cryo-unit) in the tunnel, the two transfer tables drive below the FCC-cryo-unit.

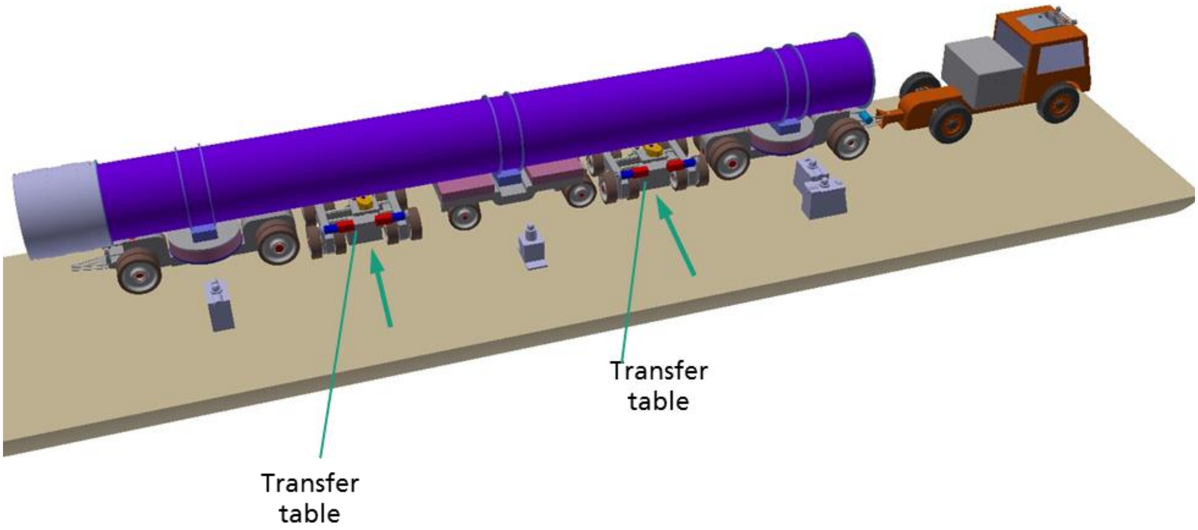


Figure 3-14: Visualisation (3) showing the use of transfer tables

The two transfer tables lift the FCC-cryo-unit and move it laterally into the assembly position of the FCC-cryo-unit.

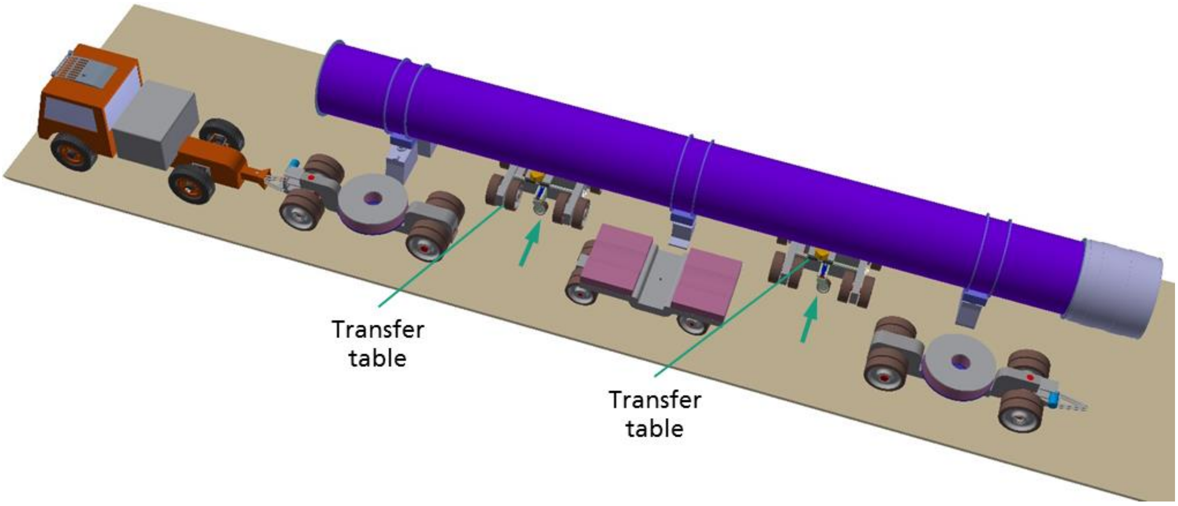


Figure 3-15: Visualisation (4) showing the use of transfer tables

The way the transfer tables work is described in more detail in subsequent chapters.

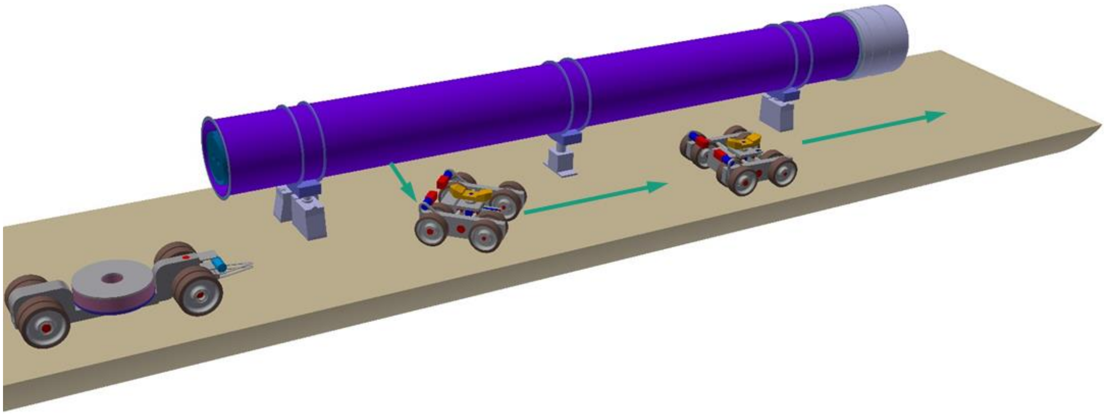


Figure 3-16: Visualisation (5) showing the use of transfer tables

After assembling the cryo-unit, the two transfer tables are moved to the next assembly position by human operators.

3.3.1 Detailed concept for transfer tables

Concept 1: Hoist based on hydraulic cylinder

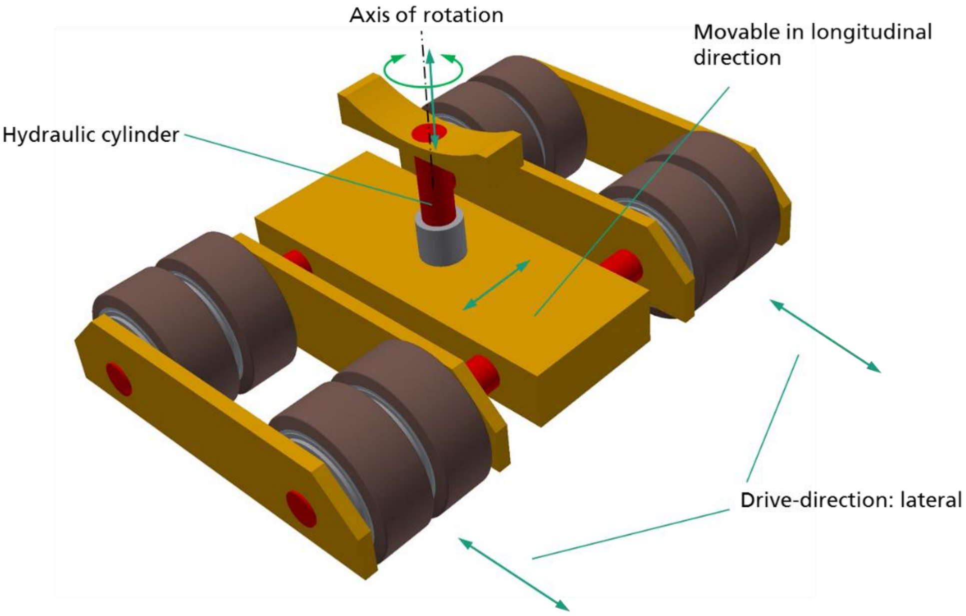


Figure 3-17: Concept for transfer tables with hydraulic cylinders

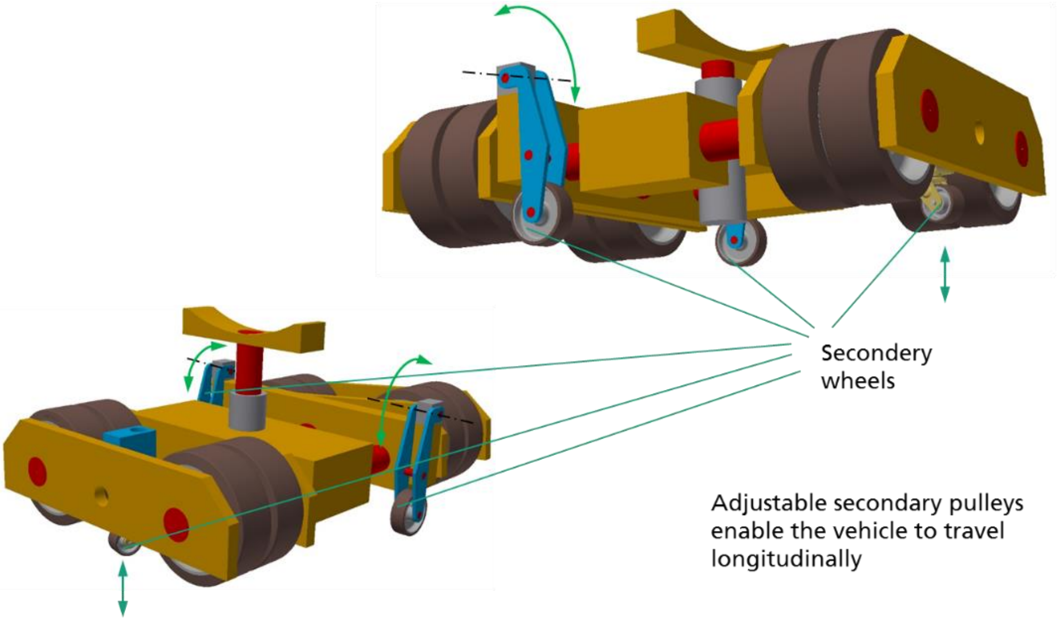


Figure 3-18: Concept for transfer tables with hydraulic cylinders and additional rollers

Auxiliary (secondary) wheels are used to move the transfer tables to the next assembly position. The auxiliary wheels are retracted manually and only used for handling the transfer tables during the unloading process.

Concept 2: Hoist based on linear cylinder (lifting cylinder)

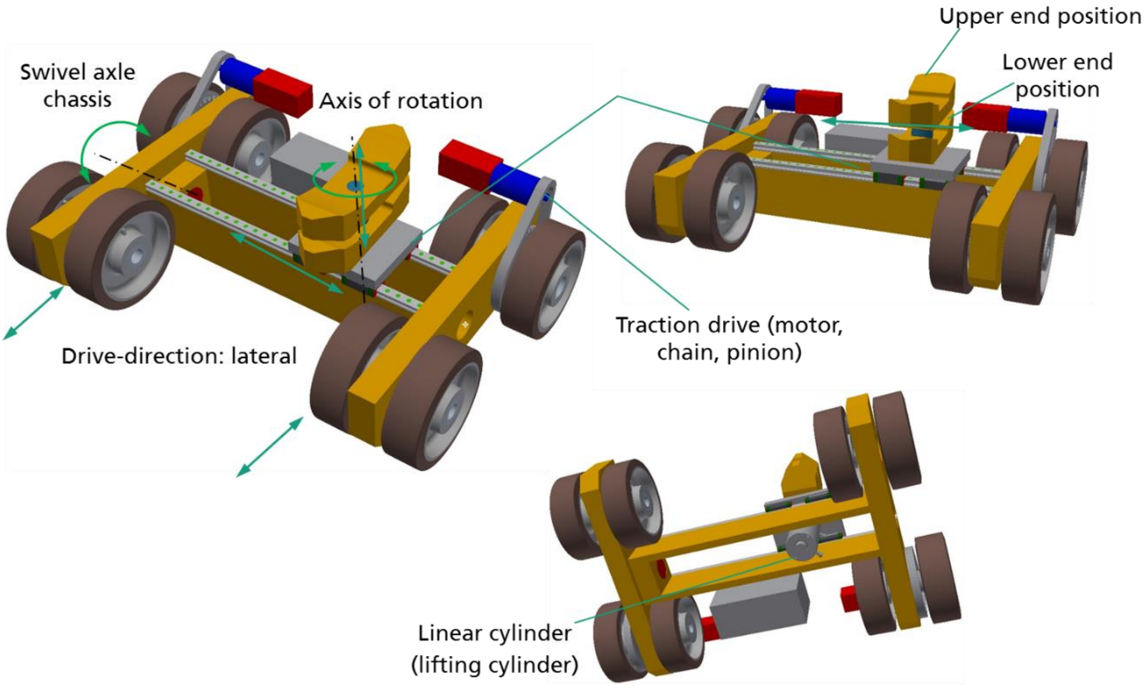


Figure 3-19: Concept for transfer tables with linear cylinders

Concept 3: Hoist based on screw jack

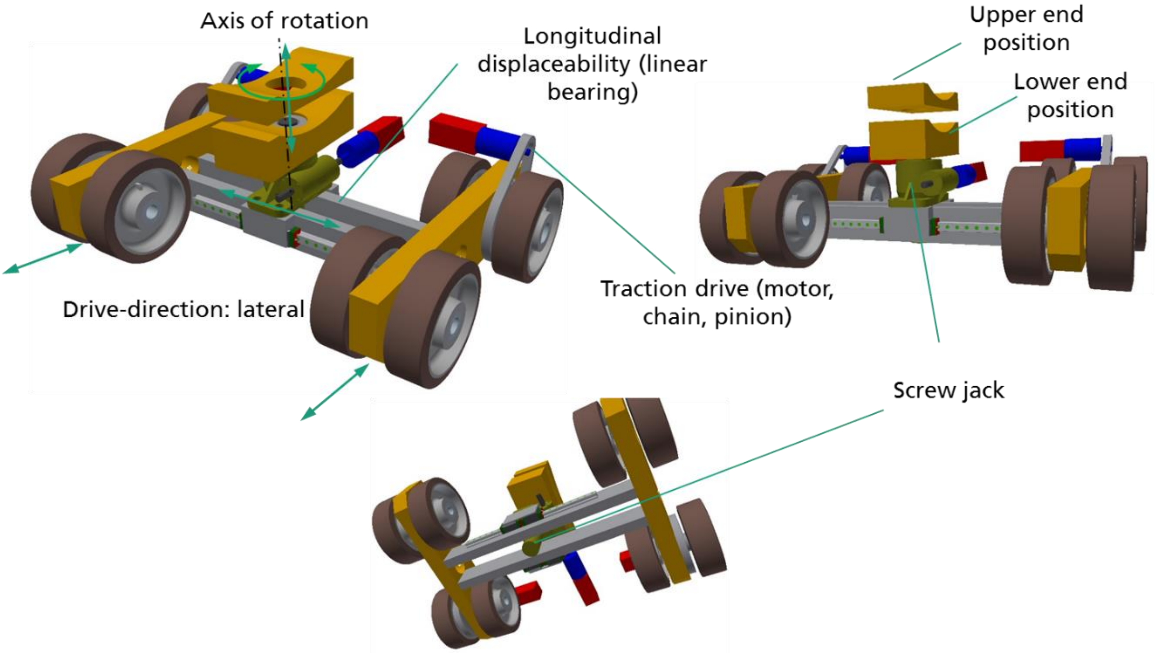


Figure 3-20: Concept for transfer tables with screw jack

3.3.2 Steering of transfer tables

The adjustable steering roller (by means of linear cylinders) means the transfer table is highly manoeuvrable.

The following need to be considered:

- Use of the roller only when in an unloaded condition
- Driven by two electric motors (concept for steering the device)

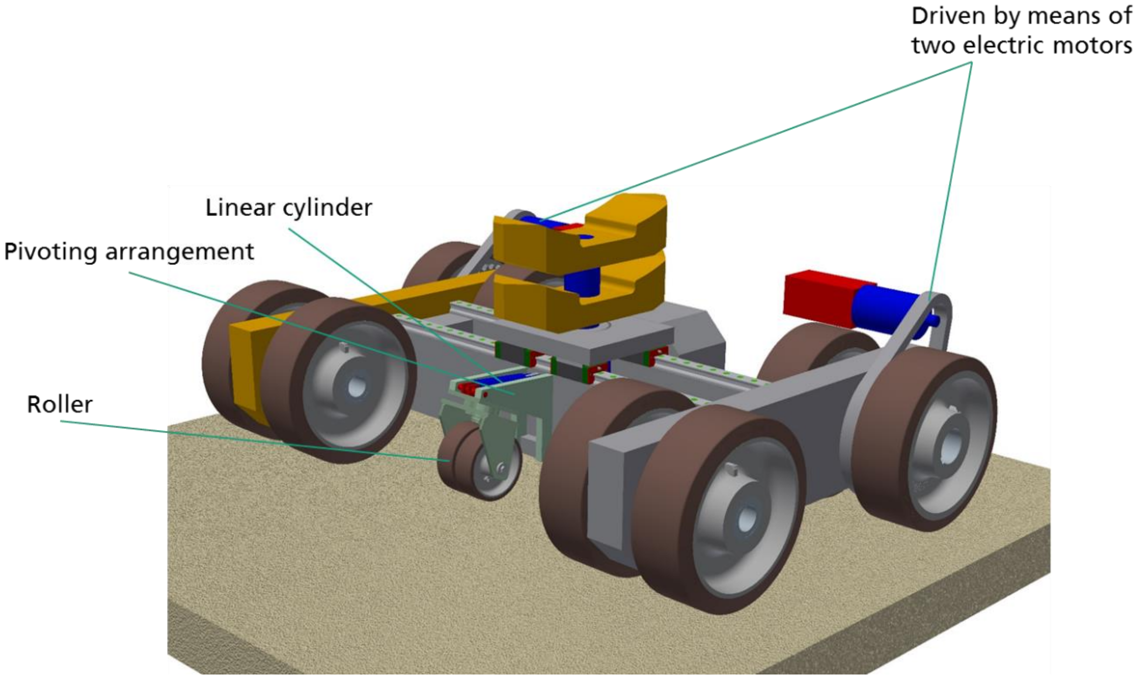


Figure 3-21: Steering concept for transfer table

The retractable roller means the transfer table is highly manoeuvrable.

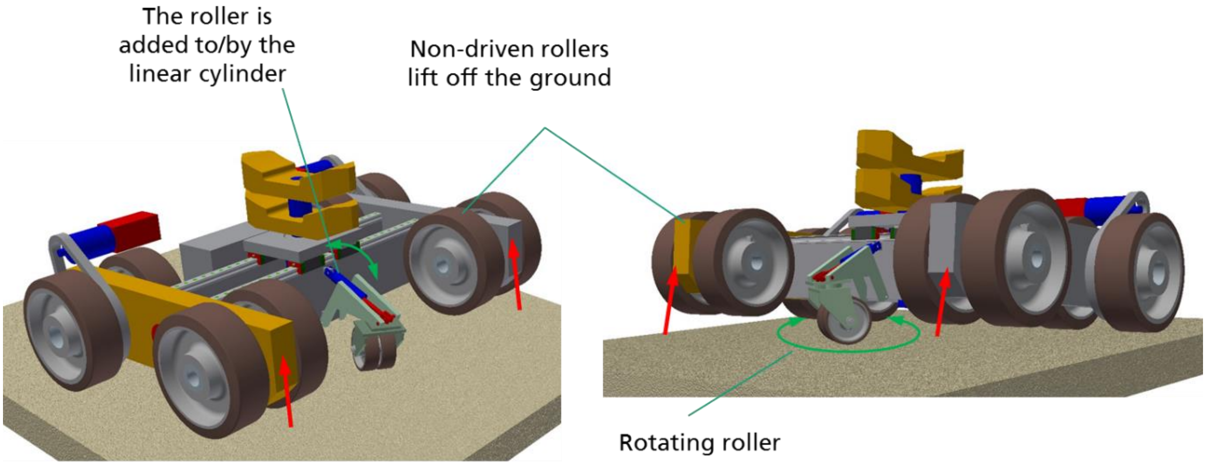


Figure 3-22: Manoeuvrability of transfer tables by means of rotating rollers

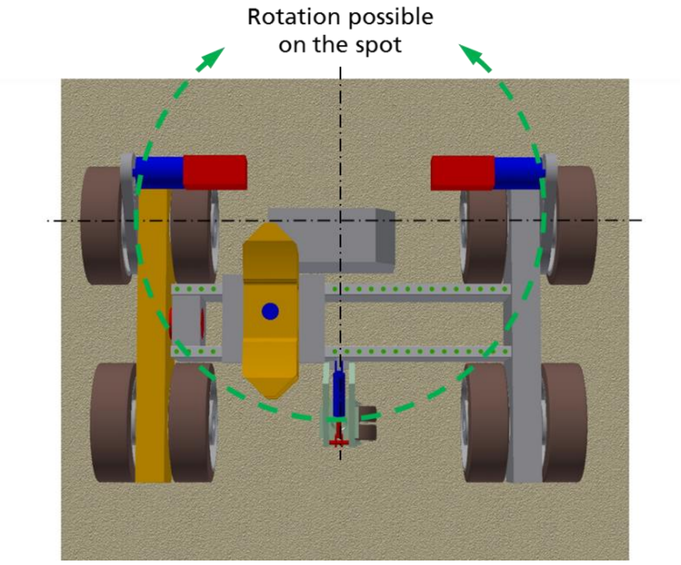


Figure 3-23: The arrangement of the drives and the use of a retractable roller means the table can rotate on the spot

3.3.3 Ground contact for transfer tables

Uneven ground compensated for by means of a flexible chassis.

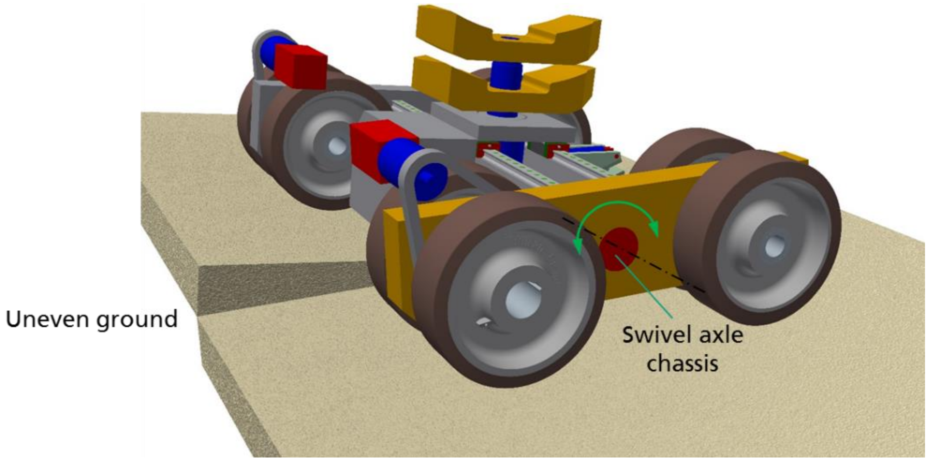


Figure 3-24: The swivel axle guarantees ground contact for all wheels even on uneven terrain

3.4 Overview of transport and handling in the tunnel

The following illustration shows the use of the planned devices in the tunnel.

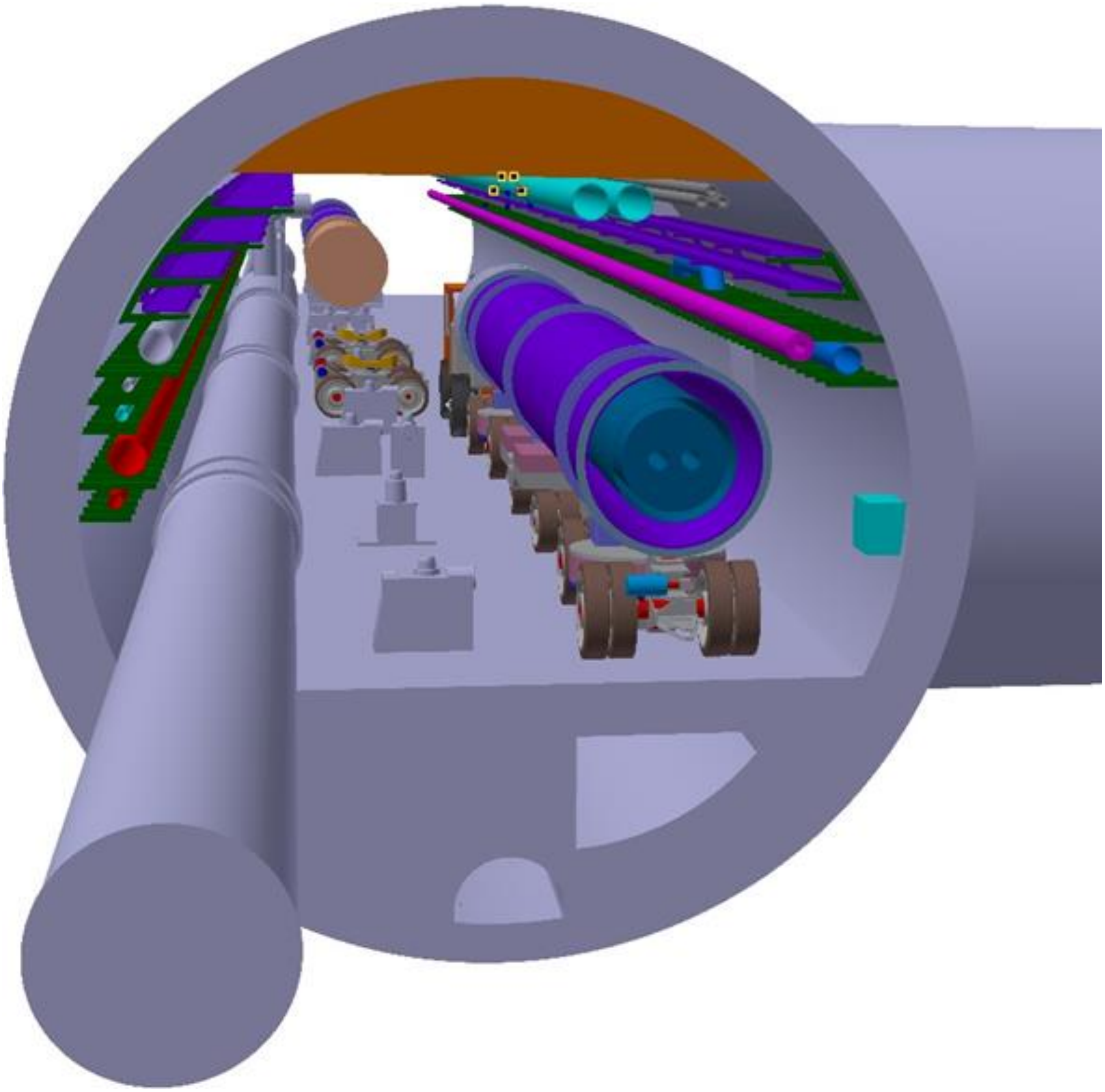


Figure 3-25: This view shows the transport and handling of a FCC-cryo-unit in the tunnel

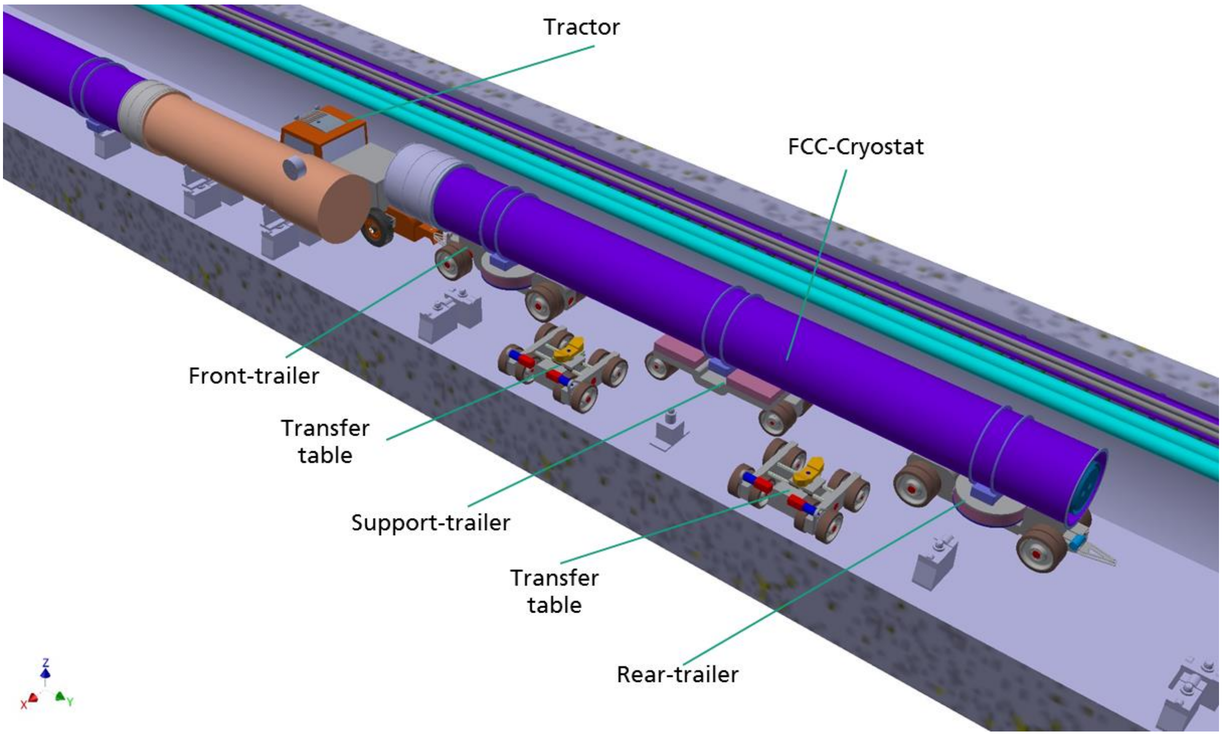


Figure 3-26: All devices that are used during transport and handling are shown in the tunnel environment

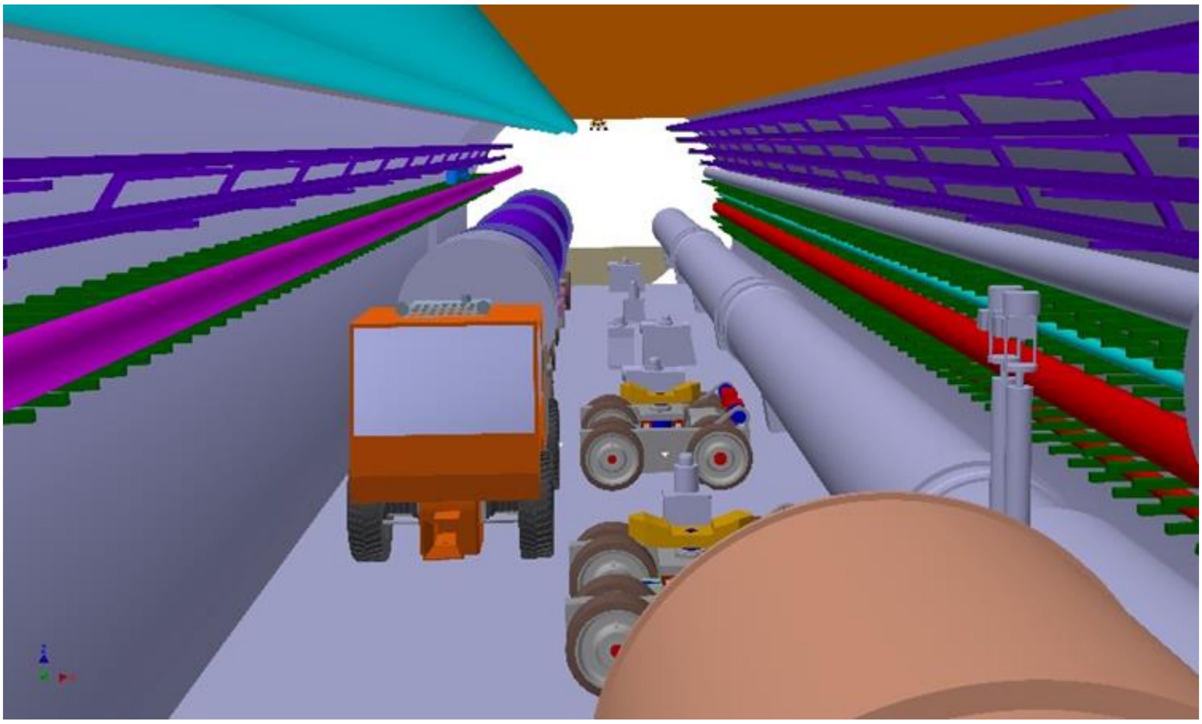


Figure 3-27: Front view of the transport process in the tunnel

3.5 Watchdog concept for transport safety in the tunnel

Currently the speed of vehicles is limited by their ability to implement emergency braking when fully loaded within the range of safety sensors. Higher velocities could be realised by the development of a "watchdog" principle, where an additional vehicle or even drone moves in front of the transport convoy in the tunnel. This watchdog scans the environment to identify possible obstacles (e.g. assembly tools, cleaning tools, building materials, etc. remaining in the tunnel) and humans on the track. If something is detected the watchdog triggers an emergency brake for the convoy so as to prevent a collision. The distance from the watchdog to the transport convoy needs to be a distance equal to or greater than the braking distance (length of the braking distance for the transport convoy from full speed to standstill).

3.6 Emergency strategy for transportation

In case there are technical failures occurring in vehicles or equipment, the following tasks have to be carried out:

- exchanging a tractor
- tractor pulling a tractor
- exchanging trailers

Special devices can be used for heavy loads in the tunnel (in case of emergency / emergency strategy).

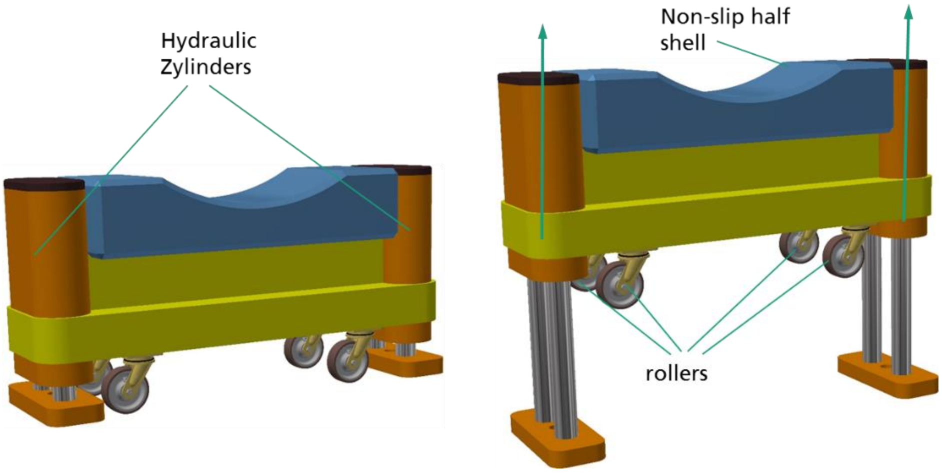


Figure 3-28: Emergency transfer tables

The emergency transfer tables use non-slippery half beds to hold the cryo-unit while it is being lifted by hydraulic cylinders. The individual units which make up the emergency system are equipped with rollers, with which the individual units can be moved and positioned.

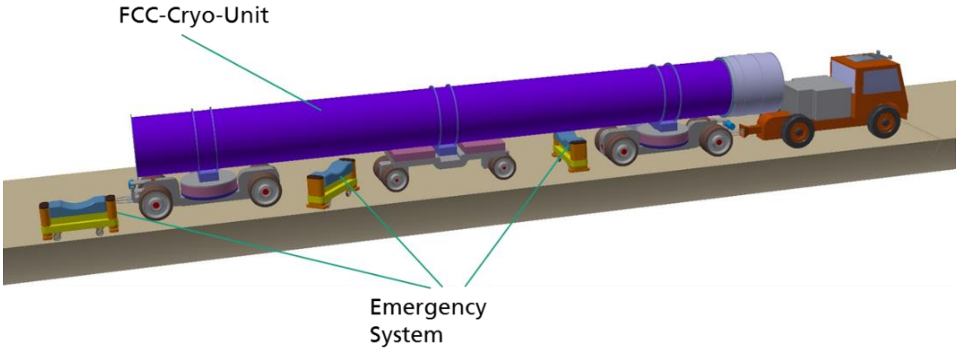


Figure 3-29: Use of emergency transfer tables (1)

The emergency system consists of movable devices that can be positioned under the load (before lifting the load) and it uses hydraulic cylinders to lift the load. After the load is lifted defective trailers can be removed and replaced. Using this approach, defective transport equipment can be replaced which guarantees transportation can continue in the tunnel.

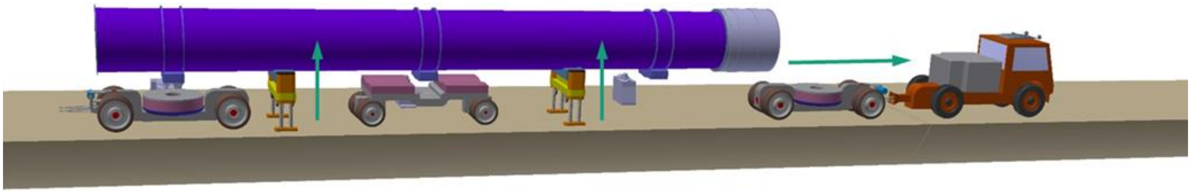


Figure 3-30: Use of emergency transfer tables (2)

4 Selection of scenarios

4.1 Investigation set-up

4.1.1 FCC process installation of cryo-units and predecessor processes

The installation of cryo-units at FCC will start at the end of November 2035 and finish at the end of November 2039. The tunnel layout divides the construction into four sections, each consisting of three sectors of different lengths - varying from 6,144 m to 9,497 m (see Figure 4-1**a**). The installation works are planned to be executed by several teams. During the cryo-unit installation phase an average of 3.7 magnets per day is needed to provide installation works with sufficient material. Demand is not distributed equally and varies from a minimum daily demand of 2.8 cryo-units to a maximum daily demand of 6.7 units (see Figure 4-1**b**).

NOTE: The magnet demand shows peaks and troughs. Balancing the demand will have a positive effect on the capacity calculated for the logistics concept. Considering the current demand derived from the construction schedule, the logistics system will have overcapacities particularly at times with less demand.

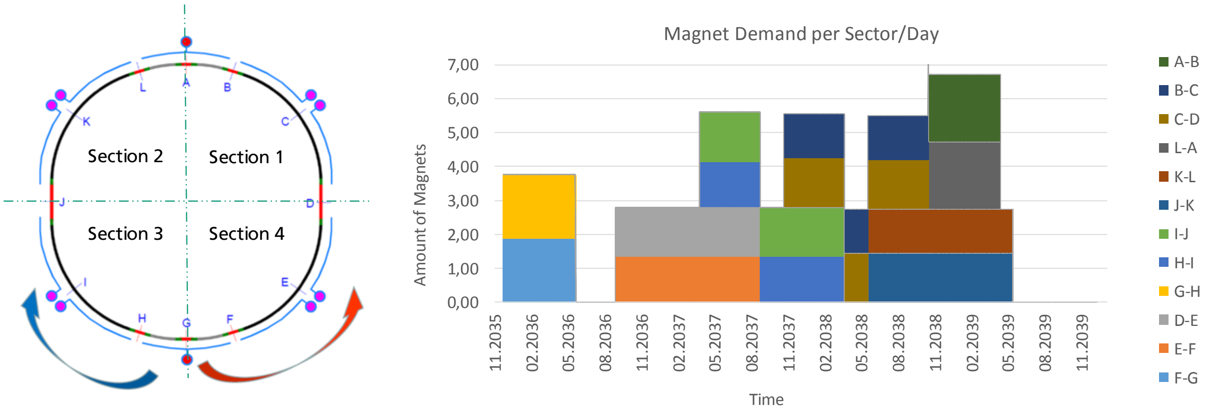


Figure 4-1: Overview Tunnel Segmentation (a) and Derived Daily Magnet Demand according to the Construction Schedule (b)

Various access shafts are planned to provide the installation work with materials (A to L, see Figure 4-1). Due to their dimension and weight, cryo-units have special transport requirements, similar to those of horizontal transports, affecting shaft width and the technical equipment at the shafts. Currently four shafts (C, E, I, K) are being designed to be magnet-transport-shafts. The suitability of selected magnet-transport-shafts is to be analysed.

NOTE: In chapter 2 different supply chain processes were introduced which need to be executed to provide the cryo-units for installation. According to the supply chain structure which is finally selected, some of the processes will not be performed by CERN. However, as the concept is not decided yet, the following investigation takes a closer look at the main process steps in the supply chain and identifies their requirements. The results will allow a very rough cost calculation. Production processes are not considered in the following investigation.

The main process steps are depicted once more in Figure 4-2. These processes can be executed by a supplier or by CERN, organized either centrally or decentrally.

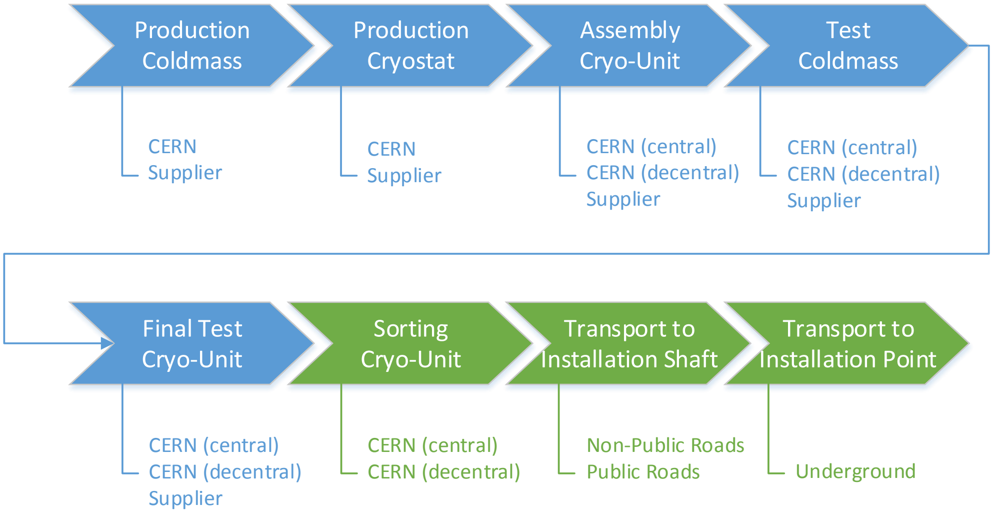


Figure 4-2: Value adding processes in cryo-unit production and CERN logistics

The aim of the following investigation is to analyse different scenarios for centrally or decentrally organized logistics by CERN. Therefore, a two-step approach was executed:

1) Identification of a valid tunnel transport scenario
2) Identification of a proper delivery strategy

To allow a scenario analysis, some assumptions are mentioned in the following which are derived from CERN or from a Logistics Study investigation e.g. figures regarding transport vehicle velocity.

4.1.2 Assumptions

To allow a scenario analysis, some assumptions are mentioned in the following, which, on the one hand, are derived from CERN, e.g. duration of testing or assembly of cryo-units. On the other hand, the input data are derived from LHC execution like coldmass testing of one cryo-unit needing five days (considering operation hours of testing facility). As cryo-units of FCC will be more complex, the investigation considers two more scenarios – testing times are increased to two or three times the duration in LHC. Other assumptions are derived from the previous analysis e.g. relevant KPIs for the transport vehicles.

Table 4-1 Overview of assumptions for tunnel transport times

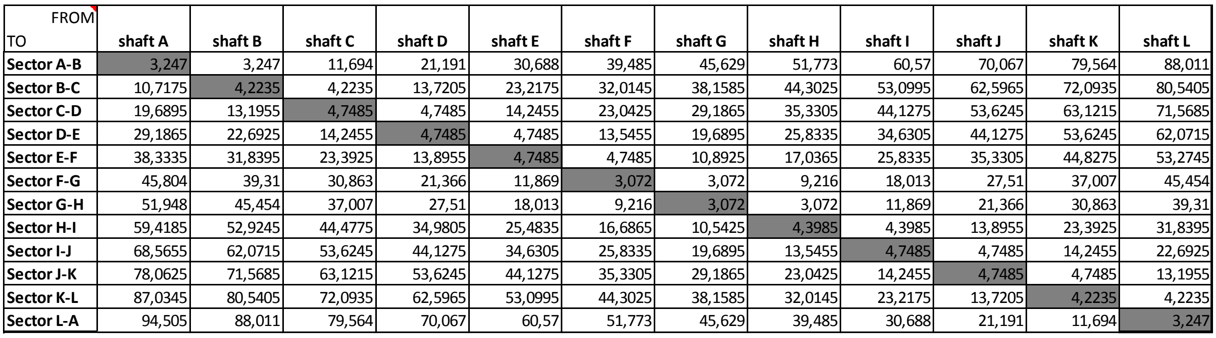
Parameter	Value
Underground transport (speed loaded)	10 km/h
Underground transport (speed unloaded)	20 km/h
Transport time interval	10 PM – 6 AM (Duration: 8 hours)
Loading time (crane transport included)	1h
Unloading time	1h
Duration assembly (LHC x1 / x2 / x3) in days	5.33 / 10.66 / 15.99
Duration coldmass test (LHC x1 / x2 / x3) in days	5 / 10 / 15
Duration final test (LHC x1 / x2 / x3) in days	0.5 / 1 / 1.5

Based on LHC execution, different shift calendars are considered for the different process steps and/or facilities (see Table 4-2).

Table 4-2: Shift Calendar

	Working weeks per year	Working days per week	Working hours per shift	# Shifts per day	Productive days per year
Assembly	50	5	8	2	250
Testing (coldmass, final)	46	7	8	3	322
Transport	52	7	8	1	365

To allow an investigation regarding the transport time and the quantity of transport vehicles that are required, the transport distances between sectors and shafts are considered. With the currently available data, an investigation is performed based on the average magnet demand per sector (on a daily basis) as well as average transport distances for the magnets in a sector. The magnet demand per sector is depicted in Figure 4-1. The transport matrix considered for the investigation is shown in Figure 4-3.



FROM TO	shaft A	shaft B	shaft C	shaft D	shaft E	shaft F	shaft G	shaft H	shaft I	shaft J	shaft K	shaft L
Sector A-B	3,247	3,247	11,694	21,191	30,688	39,485	45,629	51,773	60,57	70,067	79,564	88,011
Sector B-C	10,7175	4,2235	4,2235	13,7205	23,2175	32,0145	38,1585	44,3025	53,0995	62,5965	72,0935	80,5405
Sector C-D	19,6895	13,1955	4,7485	4,7485	14,2455	23,0425	29,1865	35,3305	44,1275	53,6245	63,1215	71,5685
Sector D-E	29,1865	22,6925	14,2455	4,7485	4,7485	13,5455	19,6895	25,8335	34,6305	44,1275	53,6245	62,0715
Sector E-F	38,3335	31,8395	23,3925	13,8955	4,7485	4,7485	10,8925	17,0365	25,8335	35,3305	44,8275	53,2745
Sector F-G	45,804	39,31	30,863	21,366	11,869	3,072	3,072	9,216	18,013	27,51	37,007	45,454
Sector G-H	51,948	45,454	37,007	27,51	18,013	9,216	3,072	3,072	11,869	21,366	30,863	39,31
Sector H-I	59,4185	52,9245	44,4775	34,9805	25,4835	16,6865	10,5425	4,3985	4,3985	13,8955	23,3925	31,8395
Sector I-J	68,5655	62,0715	53,6245	44,1275	34,6305	25,8335	19,6895	13,5455	4,7485	4,7485	14,2455	22,6925
Sector J-K	78,0625	71,5685	63,1215	53,6245	44,1275	35,3305	29,1865	23,0425	14,2455	4,7485	4,7485	13,1955
Sector K-L	87,0345	80,5405	72,0935	62,5965	53,0995	44,3025	38,1585	32,0145	23,2175	13,7205	4,2235	4,2235
Sector L-A	94,505	88,011	79,564	70,067	60,57	51,773	45,629	39,485	30,688	21,191	11,694	3,247

Figure 4-3: Transport matrix – distances in km

4.1.3 Investigation scenarios

Table 4-3 names the scenarios which are analysed in the following to identify the required quantity of transport vehicles and assembly/test facilities to adequately supply installation works. Furthermore, necessary storage capacities are calculated to support assembly/testing and installation works in a proper manner. As the supply of magnets is carried out using specific magnet-transport-shafts, these shafts were used to develop the different scenarios.

Table 4-3: Overview of investigation scenarios

Alternative	Variant		Construction shaft	Description
1	0	Central supply	A	Magnet demand for all sectors is transported via shaft A.
2	1	Decentral supply	C, K	Magnet demand section 1.4 is transported via shaft C, Magnet

				demand section 2.3 is transported via shaft K
2	2	Decentral supply	E, K	Magnet demand section 1.4 is transported via shaft E, Magnet demand section 2.3 is transported via shaft K
2	3	Decentral supply	J, D	Magnet demand section 1.4 is transported via shaft J, Magnet demand section 2.3 is transported via shaft D
3	3	Decentral supply	C, E, I, K	Magnet demand - section 1 transported via shaft C, - section 2 transported via shaft E, - section 3 transported via shaft I, - section 4 transported via shaft K,

4.2 Investigation into tunnel transport

The following Table 4-4 depicts the different alternatives for the shaft to sector assignment. Using the table, it is easy to identify which shaft is used in the different scenarios to transport the cryo-unit for a certain sector. The shaft selection has an influence on the transport distances of the vehicle, this overview is essential to understand the different investigation results.

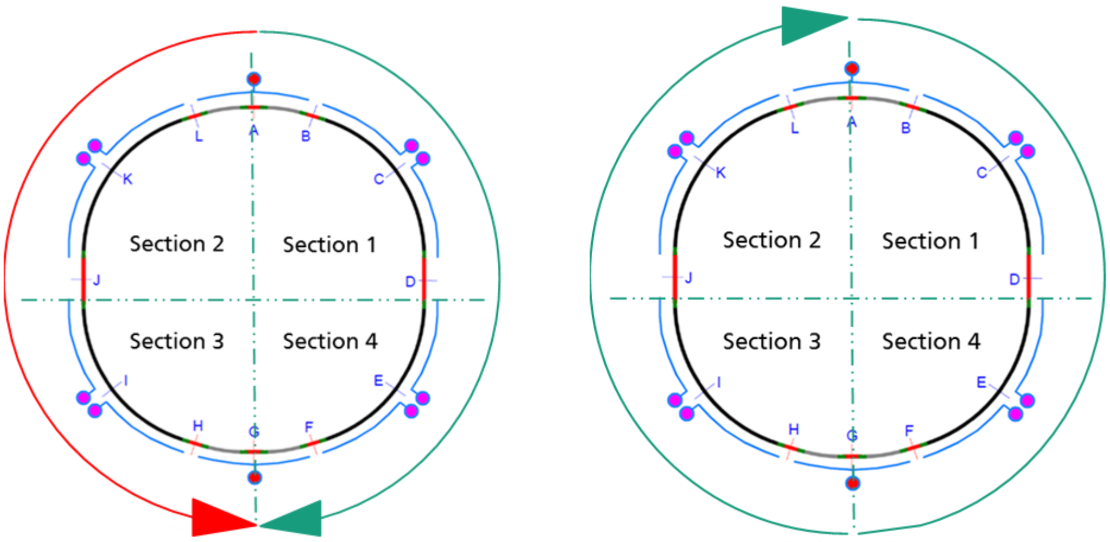
Table 4-4: Overview of assignment sector/ shaft in Alternatives

	Alternative 1.1		Alternative 1.2	Alternative 2.1		Alternative 2.2.		Alternative 2.3		Alternative 2.4		Alternative 3.1			
	A (left)	A (right)	A	C	K	D	J	E	K	E	K	C	E	I	K
Sector A-B		X	X	X		X		X			X	X			
Sector B-C		X	X	X		X		X			X	X			
Sector C-D		X	X	X		X		X		X		X			
Sector D-E		X	X	X		X		X		X			X		
Sector E-F		X	X	X		X		X		X			X		

Sector F-G		X	X	X		X		X		X			X		
Sector G-H	X		X		X		X		X	X				X	
Sector H-I	X		X		X		X		X	X				X	
Sector I-J	X		X		X		X		X		X			X	
Sector J-K	X		X		X		X		X		X				X
Sector K-L	X		X		X		X		X		X				X
Sector L-A	X		X		x		x		x		X				X

4.2.1 Alternative 1 – central supply

Alternative 1 allows us to look at two different variants of material transport within the tunnel (see Figure 4-4. The green and red arcs in Figure 4 show the magnet transport direction.



Alternative 1.1: clockwise/counter-clockwise central supply

Alternative 1.2: concentric clockwise central supply

Figure 4-4: Material flow for Alternatives 1.x

The following figure depicts the results of the transport capacity calculation for **Alternative 1.1**. The blue line depicts the magnet demand during construction time while the orange line shows the supply of transport capacity considering the number of vehicles and transport distances in the different sectors.

Assumption: 5 transport vehicles (2 vehicles per half, one additional which could be used in both halves ("jumper"))

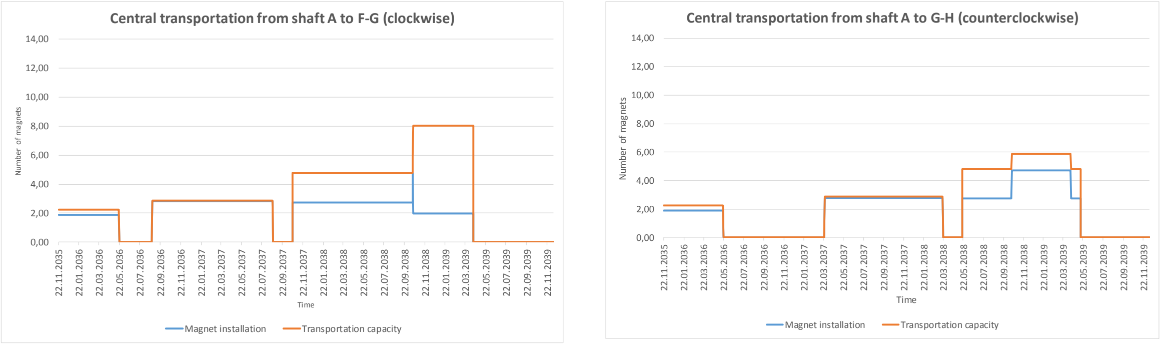
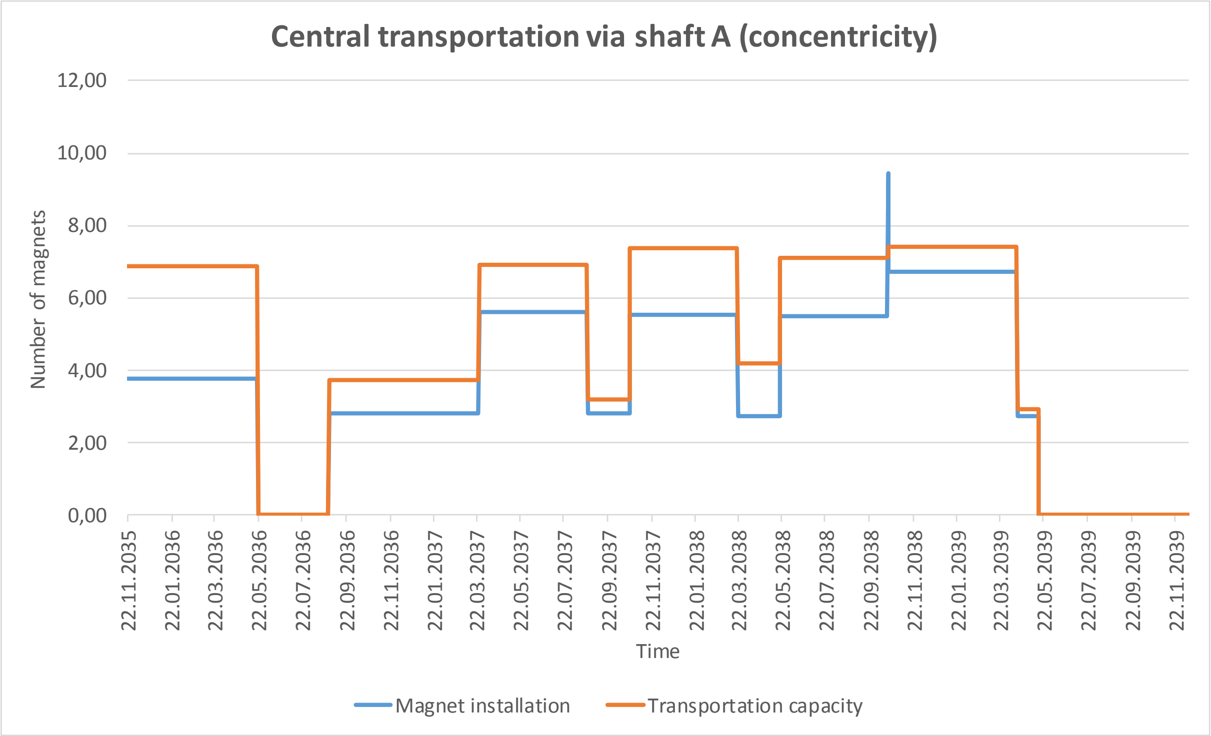


Figure 4-5: Overview of magnet demand vs. transport capacity for Alternative 1.1 for semi-cycle A to F-G (a) and semi-cycle A to G-H (b)

The following figure depicts the results of the transport capacity calculation for **Alternative 1.2**. The blue line depicts the magnet demand during construction time while the orange line shows the supply of transport capacity considering the number of vehicles and transport distances in the different sectors.

Assumption: 8 transport vehicles



(* the peak demand in September results from a one day overlapping of scheduled construction in several sectors)

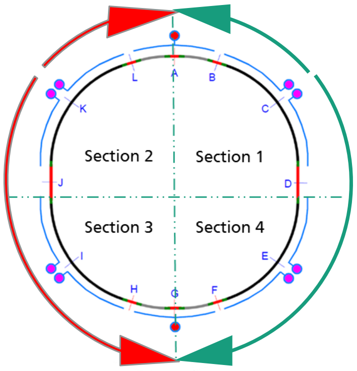
Figure 4-6: Overview of magnet demand vs. transport capacity for Alterative 1.2

Intermediate results

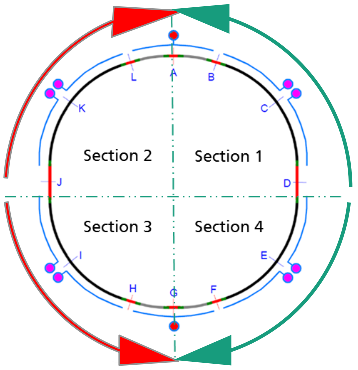
Investigation of the Alternatives 1.x show that a supply of magnet installation works through one magnet shaft is possible. However, both scenarios differ in their number of vehicles. Looking at the concentric magnet transport scenario (**Alternative 1.2**) the number of vehicles is increased but organisation of transports is very easy compared to other scenarios. In a concentricity scenario it is important to synchronize the transports so that the different vehicles will not block each other. Therefore, the vehicles with the longest transport route should be the first in line to be loaded and start. Thus, the 8 vehicles needed will be organized as a tugger train. An intended transport shift time of 8 hours together with the length of the tunnel in particular prevent the application of this scenario. As loading a vehicle will take 1 hour within the given time frame for transports at least one of the vehicles is just loaded but not transporting anything. To avoid this, loading vehicles in advance of their transport shift should be allowed. In consequence, sufficient buffer spaces for loaded vehicles must be provided inside the tunnel. On the other hand, due to the length of the tunnel (97km) and transport vehicle velocity in a loaded situation (10km/h) not all magnets can be delivered within the transport time frame. This applies especially for sectors in section 2. Thus, buffer spaces also need to be provided inside the tunnel or the driving direction of the tugger train should be changed. Looking at the construction schedule, a change of concentric direction does not currently make sense, as installation works in section 3 and 4 as well as in section 1 and 2 are performed in parallel. Thus, magnet demand in section 1 and 2 will be in the same interval. Besides the aspects discussed, a concentricity scenario has one major disadvantage and is therefore not recommended for CERN. As only one transport route is possible, this scenario is very sensitive regarding distributions. Whenever one vehicle is defect or the tunnel street itself has some damage or obstacles, all transports will be affected. Here **Alternative 1.1** is far more robust. As the supply is organized in semi-tunnel-cycles at least half of one tunnel can be delivered with magnets, even if problems occur in the second half. Alternative 1.1 needs to have tunnel vehicles that are able to drive forwards and in reverse, as it is not possible for vehicles inside the tunnel to pass each other. Even though the distance for loaded transports is reduced and vehicles can be loaded and can drive to the installation point within the transport shift, loading in advance of the shift is recommended. This is valid at least when the most distant installation points need to be supplied - to guarantee that all vehicles are able to bring their loads to the destination and return to the central supply shaft. Alternative 1.1 requires 5 vehicles. One vehicle is planned as a "jumper" which can be used on both sides. The demand-capacity-graph shows that at the beginning of construction the vehicle capacity is almost exhausted. This can be eased when the construction schedule is adapted and tasks in sector D-F and H-J do not overlap.

4.2.2 Alternative 2 – decentral supply (two shafts)

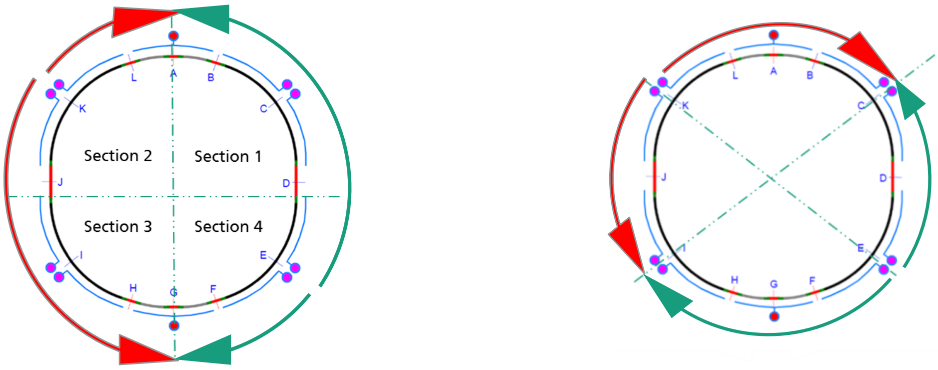
Alternative 2 allows us to look at four different variants of material transport within the tunnel (see Figure 4-7). It is based on the assumption that of the two magnet transport shafts, different ones are selected and the impacts on demand/capacity-management are investigated. Besides the 3 variants mentioned in Figure 4-7 an additional one is analysed in which an assignment of sectors was defined which deviates from alternatives 2.1-2.3. The green and red arcs in Figure 4-7 show the magnet transport direction.



Alternative 2.1: Shaft C (Section 1,4), Shaft K (Section 2,3)



Alternative 2.2: Shaft J (Section 1,4), Shaft D (Section 2,3)



Alternative 2.3: Shaft E (Section 1,4), Shaft K (Section 2,3)

Alternative 2.4: Shaft E, Shaft K - changes in the installation order are necessary (shaft E supplied I-H – C-D and shaft K supplied I-J – C-B

Figure 4-7: Material flow for Alternatives 2.x

The following figure depicts the results of the transport capacity calculation for **Alternative 2.1**. The blue line depicts the magnet demand during construction time while the orange line shows the transport capacity available considering the number of vehicles and transport distances in the different sectors.

Assumption: 4 transport vehicles (2 vehicles per shaft)

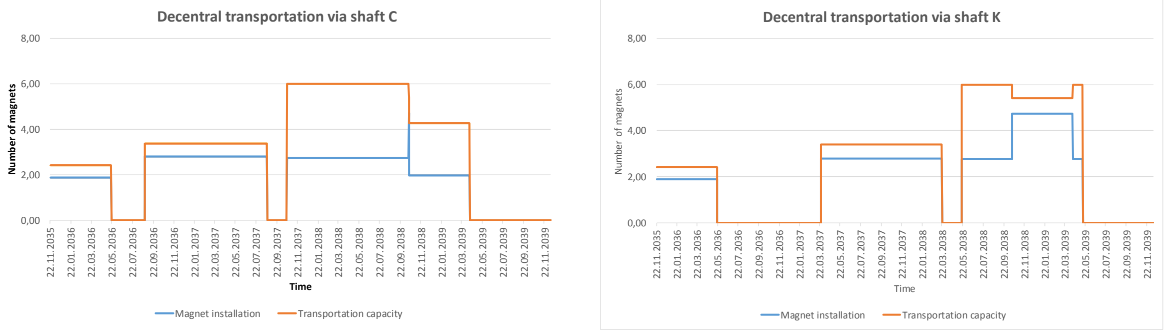


Figure 4-8: Overview of magnet demand vs. transport capacity for Alterative 2.1

The following figure depicts the results of the transport capacity calculation for **Alternative 2.2**. The blue line depicts the magnet demand during construction time while the orange line shows the transport capacity available considering the number of vehicles and transport distances in the different sectors.

Assumption: 4 transport vehicles (2 vehicles per shaft)

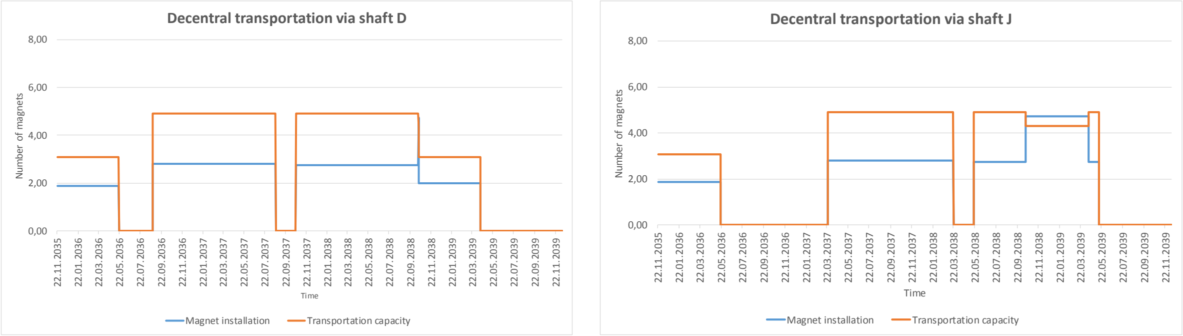


Figure 4-9: Overview of magnet demand vs. transport capacity for Alterative 2.2

The following figure depicts the results of the transport capacity calculation for **Alternative 2.3**. The blue line depicts the magnet demand during construction time while the orange line shows transport capacity available considering the number of vehicles and transport distances in the different sectors.

Assumption: 4 transport vehicles (2 vehicles per shaft)

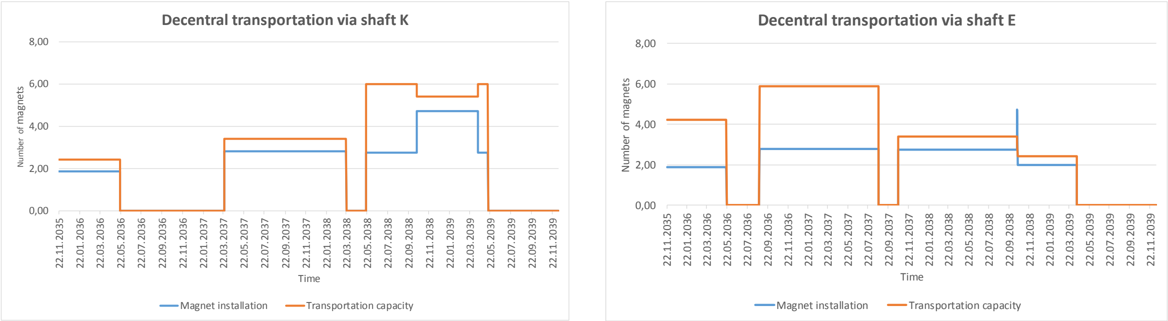


Figure 4-10: Overview of magnet demand vs. transport capacity for Alterative 2.3

The following figure depicts the results of the transport capacity calculation for **Alternative 2.4**. The blue line depicts the magnet demand during construction time while the orange line shows transport capacity available considering the number of vehicles and transport distances in the different sectors.

Assumption: 6 transport vehicles (3 vehicles per shaft)

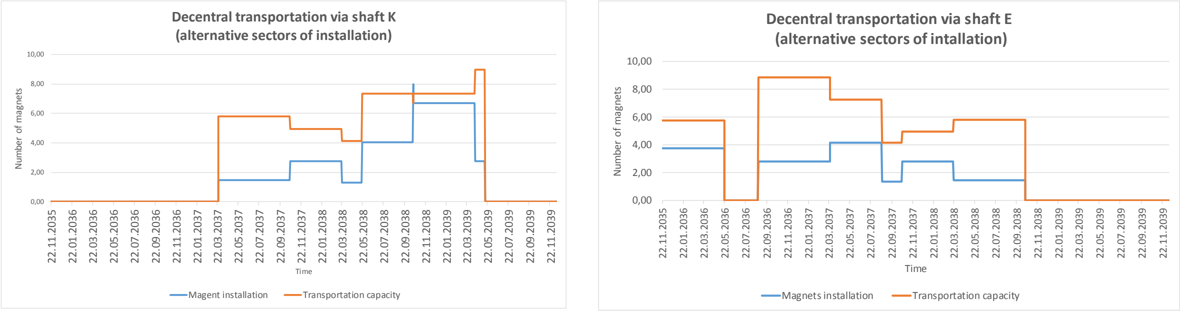


Figure 4-11: Overview of magnet demand vs. transport capacity for Alterative 2.3

Intermediate results

Alternatives 2.x show that the two shaft scenarios in 1-3 only need 4 vehicles, and throughout the installation period the transport vehicles have spare capacity. The scenarios evaluate supply via two shafts in tunnel-semi-cycles and are very similar to alternative 1.1. However, providing a second shaft means it is possible to avoid the risk that can occur in Alternatives 1.x where disturbances in the central supply shaft or its equipment mean supply for the whole construction must stop and magnet installation is delayed. Delays in the construction schedule resulting from an interrupted magnet supply probably cannot be compensated for since installation teams must be highly trained and capacities cannot be increased ad-hoc. Alternative 2.1 shows a scenario where installation shafts are located close to the CERN area. The advantage of this is that some of the assembly and testing facilities can be located centrally at CERN and dimensioned so they can supply both parts of the construction site. Transport routes from the CERN area to the shafts are relatively short. As the figure shows, the transport routes to the different sectors are not equal and therefore transport capacity is not utilized equally. This means that the second construction phase has significant overcapacity. This changes in alternative 2.2 but the total number of vehicles needed cannot be reduced. In alternative 2.3, two shafts located opposite each other are analysed. The demand-capacity-graph shows that overcapacities are shifted. In the semi-cycle delivered by shaft E vehicles, overcapacities arise in the first construction phase due to short transport distances to supply sectors D-F. The second semi-cycle delivered by shaft K shows a different picture. Here in the second construction phase, overcapacities arise due to the short transport distances to sectors A-J. Due to an equal capacity utilization from a logistical point of view, alternative 2.2 is preferred. However, shafts E and K are the ones with the shortest shaft height which affects the construction costs. Thus, a fourth alternative is evaluated to combine the advantages from both scenarios. The evaluation of alternative 2.4 shows that 6 vehicles are necessary to guarantee magnets are supplied in time. As the construction schedule was not adapted, the magnet demand is unequally distributed and therefore the positive effects of alternative 2.2 do not arise. To diminish the number of vehicles in alternative 2.4, the construction schedule must be adapted so that construction test sectors are located around shaft I and construction works in subsequent sectors are scheduled successively. Looking at the over ground logistics and infrastructure alternatives, 2.2 – 2.4 do involve some disadvantages. When central assembly and testing facilities are provided, the over ground transport routes to the shafts are longer than in alternative 2.1. To avoid this, decentral facilities at the shafts will need to be set up.

4.2.3 Alternative 3 – decentral supply (four shafts)

Alternative 3 allows supply via four shafts to be investigated. Here, section 1 is supplied by shaft C, section 2 is supplied by shaft K, section 3 is supplied by shaft I and section 4 is supplied by shaft E.

The following figure depicts the results of the transport capacity calculation for **Alternative 3.0**. The blue line depicts magnet demand during construction time while the orange line shows transport capacity supply considering the number of vehicles and transport distances in the different sectors.

Assumption: 4 transport vehicles (1 vehicle per shaft)

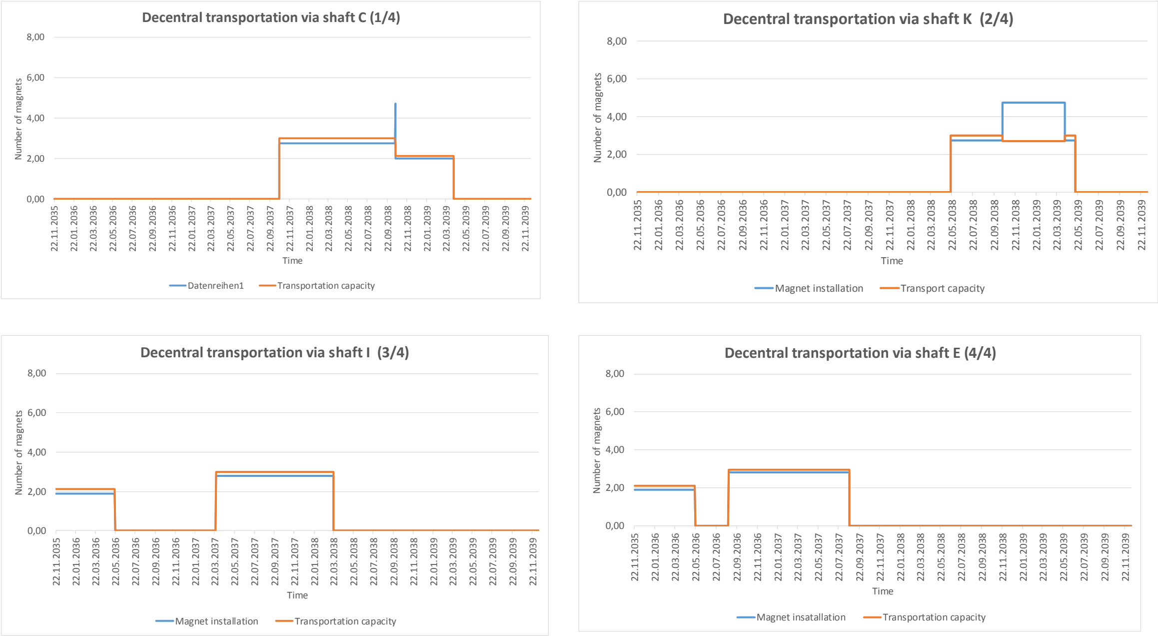


Figure 4-12: Overview of magnet demand vs. transport capacity for Alterative 3.0

The presented solution of 1 vehicle per shaft including in shaft K is only valid if the demand curve can be balanced. Thus, peak demand should be shifted prior to May 2038 or after May 2039. Otherwise, the use of 2 vehicles in shaft K is required.

Intermediate result

Supplying the installation works using four shafts is currently what is being planned and discussed by CERN. The analysis shows that this scenario will work for most of the shafts with one vehicle. As the magnet demand per sector is always less than 2 magnets per day and transport distances within one section are relatively short, one vehicle is sufficient. The exception is section 2, where magnet demand increases up to 5 per day. Here a rescheduling and redistribution of tasks should be considered, or a second vehicle provided. For alternative 3, it seems a central location for assembly and testing facilities is not a valid solution due to the long transport distances for at least half of the magnets. Decentralized assembly and testing facilities are necessary here which leads to increased costs.

4.2.4 Intermediate result – transport scenarios

The following Table 4-5 shows the necessary number of tunnel transport vehicles in the different alternatives presented.

Table 4-5: Overview of the necessary number of transport vehicles

Alternative	Total number of transport vehicles
Alternative 1.1	5
Alternative 1.2	8
Alternative 2.1	4
Alternative 2.2	4
Alternative 2.3	4
Alternative 2.4	6
Alternative 3.1	5

Alternative 1.2 (Central supply via one shaft A and concentricity) requires the highest number of transport vehicles. Furthermore, this alternative is prone to disruptions. Whenever the transport path is disturbed, e.g. by damage or broken-down vehicles, the whole supply concept is affected. All other alternatives presented here can be executed using 4-6 vehicles. To diminish overall costs, a reduction in magnet transport shafts is recommended and the analysis shows that a reduction to at least one magnet transport shaft is possible (Alternative 1.1). However, this alternative is also prone to disruptions. As supply of the construction sections is possible in both directions (clockwise, counterclockwise) disturbances like damage or obstacles on the transport route can be compensated for, but other disturbances which are connected to shaft supply, e.g. crane failure, will result in a complete interruption of supply or work in the tunnel. To diminish the susceptibility to these interferences it is recommended to construct at least two magnet transport shafts. The choice of shafts depends, among other things, on the available space required for assembly and testing equipment.

4.3 Investigation into assembly, testing and storage capacities

On the basis of the tunnel transport scenario investigation, the over ground supply of material is investigated in the following. Like in the previous investigation a varying number of magnet transport shafts is considered, resulting in a varying number of assembly and testing facilities. Testing the magnets in advance of the installation phase should be avoided as should high inventory levels. The number of testing facilities and duration of testing processes has a strong influence on these factors. As testing duration is not clear yet, the following investigation considers testing times according to LHC (LHC-testing time x1; LHC-testing time x2; LHC-testing time x3). As coldmass tests are the bottleneck, the investigation was executed "only" looking at these test facilities and test times.

__NOTE:__ The planning aim at LHC was to enable synchronized assembly and coldmass tests for magnets. Thus, the resulting duration of assembly and testing processes are almost equal. Nevertheless, the shift times for assembly and testing were different. Assembly capacity could be increased by arranging longer shift times, but the testing facilities were at their upper limit. If we transfer the results to FCC logistics, the reader should *keep in mind that we must balance the output of assembly lines and testing facilities to achieve synchronized processes.*

4.3.1 Alternative 1 – central supply

Alternative 1 assumes that magnet installation process is supplied via one shaft (shaft A, close to the CERN area). So, magnet demand is delivered using one magnet transport shaft. The magnet demand for this alternative is given in Figure 4-1.

Assumption: 25 Coldmass Test Benches

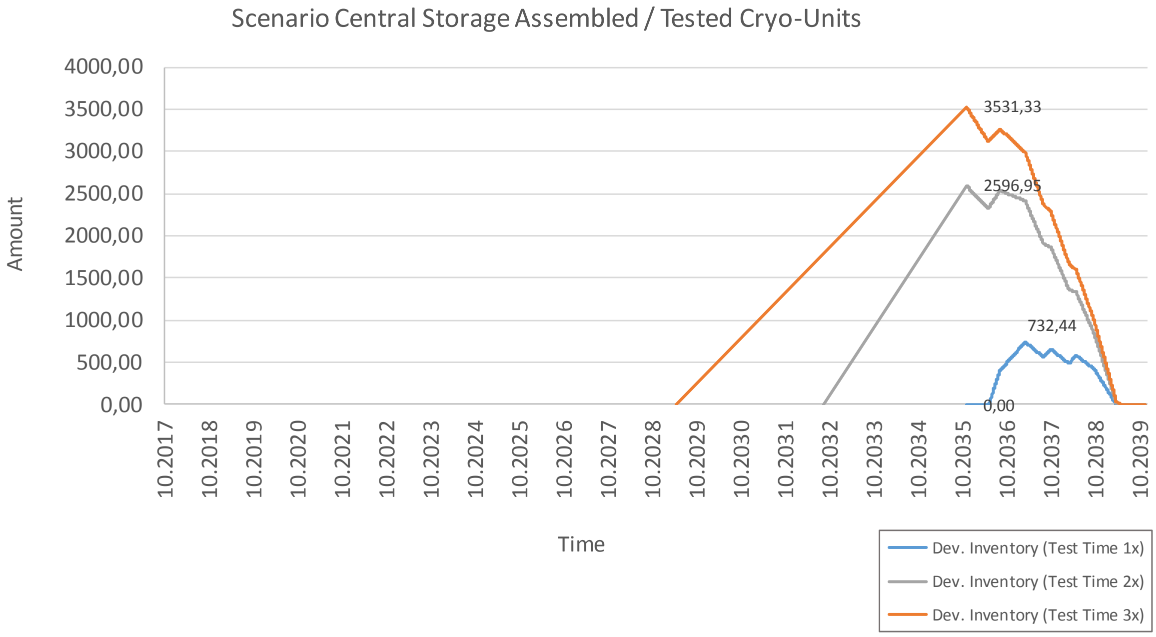


Figure 4-13: Storage Capacity Demand considering different coldmass testing times and 25 benches for coldmass tests

With assumed coldmass testing times of 1x LHC (5 days) and with the facility shift times (see Table 4-2), a minimum of 25 test benches must be provided to avoid needing coldmass testing before starting magnet installation and to guarantee that the site can always be delivered with tested magnets. (Looking at the average demand of 3.7 magnets per day, it shows that within the 5 days of testing nearly 20 magnets are required.) The magnet demand is not balanced and overcapacities during the installation phase will be used to pre-test magnets and store them. This makes it possible to supply the site in times of higher demand than could be satisfied with 25 test benches from stock. To achieve this, magnet storage for 730 magnets should be provided near the magnet transport shaft.

The central supply alternative has the advantage of proximity to the CERN area. Thus, existing infrastructure can be re-used for FCC and storage areas will be available.

4.3.2 Alternative 2 – decentral supply (two shafts)

Alternative 2 assumes the magnet installation process is supplied via two shafts. In this analysis, shafts C and K are selected as decentral shafts. To ensure short transport distances for tested magnets the following investigation assumes decentral assembly and testing facilities. The magnet demand is distributed over the two supply shafts as shown in the graph below.

Figure 4-14: Shaft-related magnet demand with decentral supply

Assuming: 24 Coldmass Test Benches (12 per shaft)

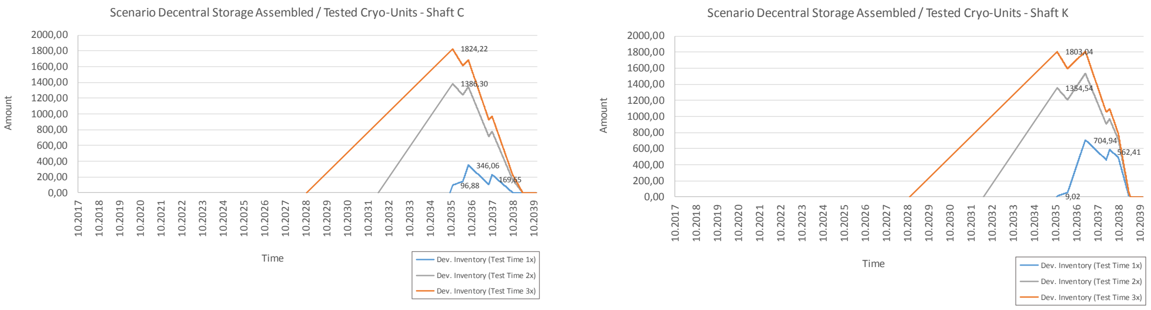


Figure 4-15: Storage capacity demand at the two shafts considering different coldmass testing times and 12 benches for coldmass tests at each shaft

With assumed coldmass testing times of 1x LHC (5 days) and with the facility shift times (see Table 4-2) a minimum of 24 test benches in total must be provided to avoid needing coldmass testing before starting magnet installation and to guarantee that the site can always be supplied with tested magnets. Each shaft gets its own facilities – at least its own coldmass and final test facilities – to avoid long transportation routes for tested magnets on public roads. At each shaft 12 test benches need to be installed to avoid needing to carry out testing in advance of the installation phase. As this quantity is not sufficient in times with high magnet demand, idle times of construction are used to build up a stock of tested magnets. To this end, at each shaft additional storage capacities are necessary. Due to magnet demand in both semi-cycles differing at shaft C a storage capacity of 350 magnets is necessary and at shaft K a capacity of 700 magnets.

Compared to alternative 1 the advantages of re-using existing infrastructure at CERN do not apply. All facilities need to be newly built from scratch. But as facilities are distributed the supply risks due to testing shortfalls are diminished in this scenario.

4.3.3 Alternative 3 – decentral supply (four shafts)

Alternative 3 assumes the magnet installation process is supplied via four shafts – C, K, E, I. The following figure depicts the magnet demand for the four sections of the tunnel.

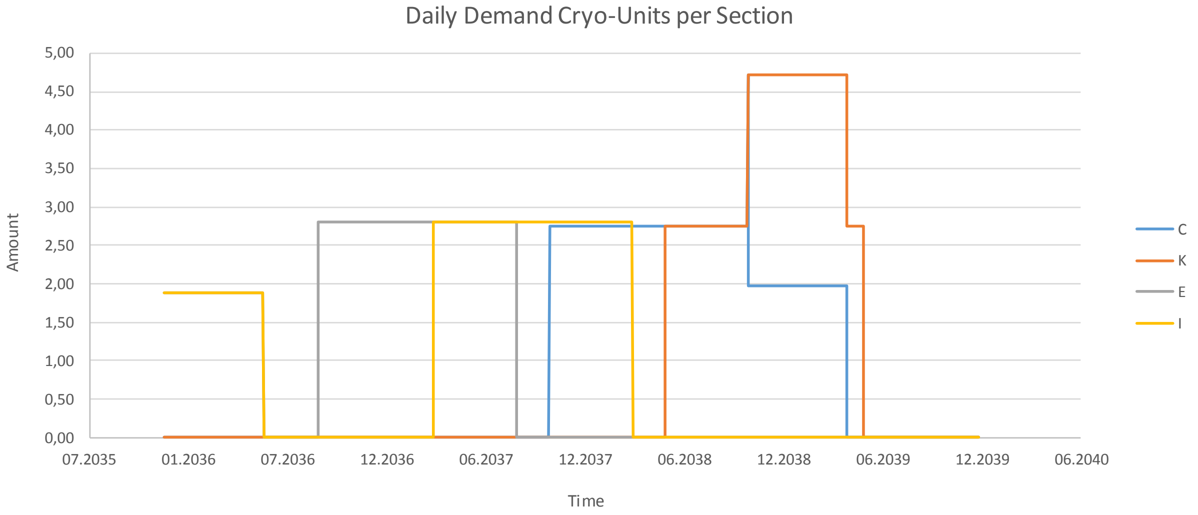


Figure 4-16: Shaft-related magnet demand for decentral supply (four shafts)

Assuming: 34 coldmass test benches (shaft C – 6 coldmass test benches; shaft E – 12 coldmass test benches; shaft I – 10 coldmass test benches; shaft K – 6 coldmass test benches)

Figure 4-17: Storage capacity demand at the four shafts considering different coldmass testing Ttmes and a total of 34 benches for coldmass tests

Compared to Alternative 1 and 2 the number of test facilities is increased due to an unequal distribution of magnet demand. With assumed coldmass testing times of 1x LHC (5 days) and with the facility shift times (see Table 4-2) a minimum of 34 test benches in total must be provided to avoid needing coldmass testing before starting magnet installation and to guarantee that the construction site can always be supplied with tested magnets. As in alternative 2, each shaft needs its own facilities to avoid long transportation routes for tested magnets on public roads. At shafts C, E, I 6 test benches are installed while at shaft K 12 test benches must be installed to avoid needing testing in advance of the installation phase. Even in this scenario idle times need to be used to build up a stock of tested magnets and at each shaft additional storage capacities are necessary - shaft C (800), shaft E (285), shaft I (360) and shaft K (950).

Alternative 3 is very robust in case of shortfalls but also means an increased need for infrastructure. Besides, the same quality standards need to be guaranteed throughout all facilities so the organisational effort would be increased in this scenario as well.

Table 4-6: Overview of alternatives needed Number of Test Benches to avoid pretesting of magnets and Max. Storage Capacity (considering different Coldmass Test Times)

Alternative		A1	A2		A3			
Coldmass test times considered	Shaft		C	K	C	K	E	I
1x LHC (5 Days)	# Coldmass Test Benches	25	12	12	6	6	12	10
	Max. Storage Capacity	738	350	707	777	968	246	374
	# Coldmass Test Benches	49	24	24	12	12	23	17

2x LHC (10 Days)	Max. Storage Capacity	805	350	707	777	968	278	469
3x LHC (15 Days)	# Coldmass Test Benches	73	36	36	18	17	34	25
	Max. Storage Capacity	827	350	707	777	989	289	480

4.3.4 Intermediate result – scenarios for assembly, testing and storage

The following table summarizes the required number of test benches and the amount of storage capacity for the analysed scenarios.

Table 4-7: Overview of Alternatives with the number of test benches required to avoid needing pretesting of magnets and max. storage capacity (considering different coldmass test times)

Alternative		A1	A2		A3			
Coldmass test times considered	Shaft		C	K	C	K	E	I
1x LHC (5 Days)	# Coldmass test benches	25	12	12	6	6	12	10
	Max. storage capacity	738	350	707	777	968	246	374
2x LHC (10 Days)	# Coldmass test benches	49	24	24	12	12	23	17
	Max. storage capacity	805	350	707	777	968	278	469
3x LHC (15 Days)	# Coldmass test benches	73	36	36	18	17	34	25
	Max. storage capacity	827	350	707	777	989	289	480

As the analysis focuses on the bottleneck process of coldmass testing, in the following the related numbers of facilities for assembling and final testing are presented. On the basis of assumed process times (see **Table 4-1**) the following numbers for facilities are derived by considering as high a throughput as coldmass testing can achieve with a calculated number of test facilities.

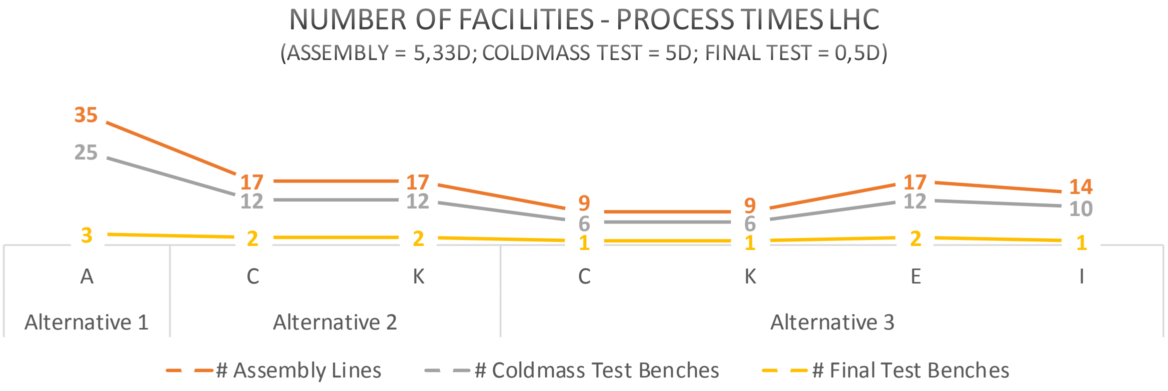


Figure 4-18: Overall overview of the number of assembly and test facilities within the different Alternatives with LHC process times

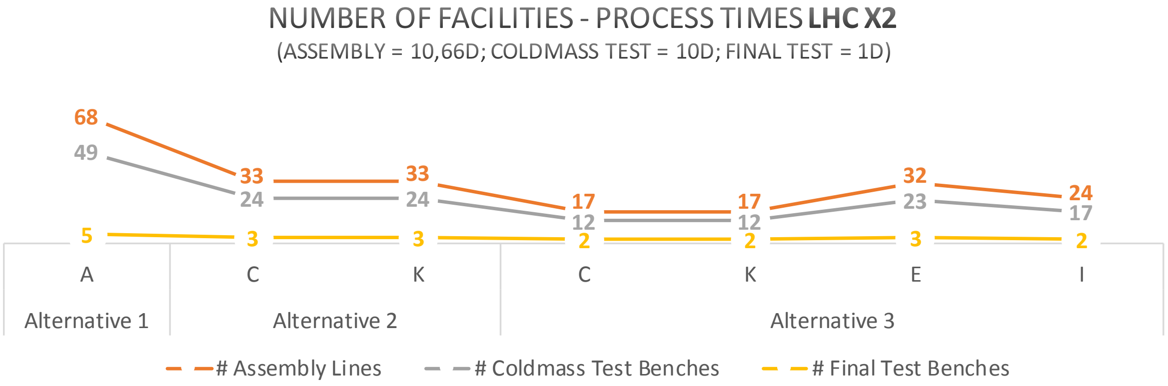


Figure 4-19: Overall overview of the number of assembly and test facilities within the different Alternatives with doubled LHC process times

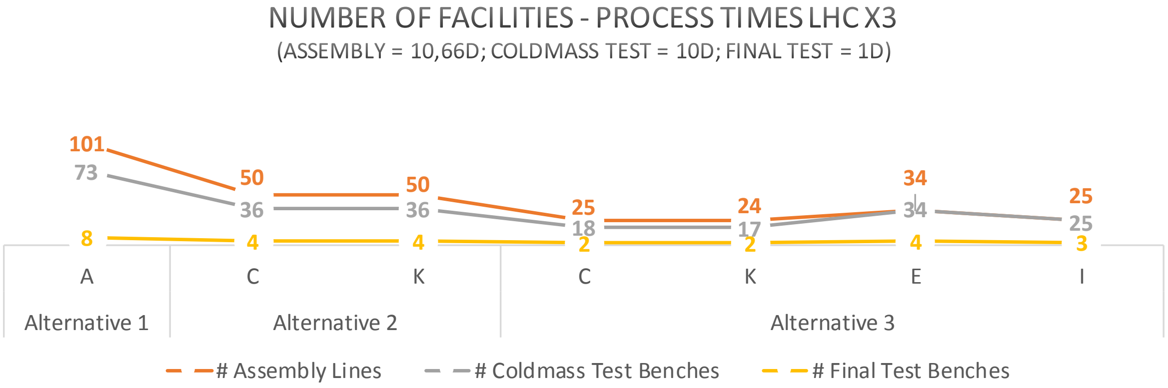


Figure 4-20: Overall overview of the number of assembly and test facilities within the different Alternatives with 3-times the LHC process times

The graphs depict the minimum quantity of facilities for the different supply alternatives considering different process times for assembly, coldmass and final testing. In total, the number of facilities for alternative 1 and 2 is equal, in Alternative 3 the overall total number of facilities is dramatically increased and should be avoided.

5 Conclusion

The results from the above chapters in general show that, from a logistics point of view, it is possible to implement FCC with currently existing technologies.

Considering the fact that proper infrastructure for the production of coldmass as well as for cryostats is currently not available at CERN, outsourcing cryo-unit production seems to be a valid solution to avoid high costs for infrastructure. Furthermore, building up a production line in Switzerland will result in high labour costs which could be shifted and decreased when value added processes are outsourced. Outsourcing processes seems to be a valid solution to avoid these costs. However, as the final product has neither been designed nor engineered yet, there are currently no suitable suppliers. CERN has to think about various concepts for supplier integration so as to establish which suppliers would be suitable. Due to the fact that the final product is very specific, the development of a suitable business model and finding multiple suppliers might be very difficult. Therefore, an intense integration of one supplier (single sourcing) is suggested. To prevent the risk of delivery insecurities the location of the supplier should be "close" to CERN to avoid long transport distances via ship. From a logistics perspective, a consideration of logistics standards throughout the product design phase, e.g. for standard transport container dimensions, is also recommended to minimise the risk of damage and reduced product quality as well as to reduce overall logistics costs.

The following recommendation should be taken into account for all transport issues of cryo-units: If possible cryo-units and other components should be designed in a way that they either a) are much more robust against transport stresses – e.g. withstand at least repeated shocks of 1g and higher – or b) that they are fitted with transport restraints that are applied during transport and can be removed after arriving at their final destination. This would help the units to withstand the minimum shocks of 1g during transport. If it is possible to fortify the cryo-units against transport stresses (by one of the above-mentioned options), also intercontinental transport of completely built up cryo-units is possible. In general, the expected transport costs for complex assemblies are between 1% and 10% of the equipment/assembly costs.

A central strategy is favoured for supplying the FCC. A central shaft close to the CERN area makes it possible to centralise assembly and testing facilities and existing infrastructure can be re-used for FCC. Furthermore, necessary storage capacities for tested magnets can be provided at the CERN area. From a qualitative perspective, a central supply is favoured. This also applies as it makes it possible to deliver similar testing circumstances for all magnets and short transport routes on public roads for tested magnets. However, central supply through only one shaft is prone to disruptions. E.g. whenever the transport crane fails, all installation works will stop. Therefore, the favoured solution is a second shaft opposite the central one (shaft A) which can be used as a backup shaft to prevent the risk of blocking. This would help to avoid "long" surface transports that could negatively influence the product quality because of shocks and vibration during transportation. However additional facilities would be needed at the opposite shafts too.

Annex A Experiences and best-practices from applied research and large industry projects

This chapter summarises the experiences and best practices Fraunhofer IML has collected in many industry projects. During the work on the FCC study, several ideas and solutions came up in numerous discussions between CERN and the Fraunhofer team. The following remarks are of course not only related to logistics and should be regarded as out-of-the-box thinking from CERN-outsiders.

A.1 Implementation of multi-tier-supplier-management for complex supply networks

In the past, only a limited number of technical components for CERN were produced directly by industrial partners. Normally, all development and prototyping were done by CERN scientists or research partners from universities due to the cutting edge (and beyond) technical solutions which are needed to operate the LHC.

Considering the size and complexity of FCC, this procedure will no longer be an option because of the limited availability of free space and skilled workforce around CERN. Therefore, industrial partners (worldwide) have to be able to supply ready-to-use (or ready-to-test) components for the FCC. This will change the currently used LHC approach into multi-tier-supplier-management including the definition of technical specifications, standards, readiness-level and quality level. The complexity of coordinating global flows of goods and materials will also increase. Some best practices can be found at large original equipment manufacturers (OEM), e.g. automotive or pharmaceutical companies.

This new supplier model can possibly lead to a rethink of traditional contributions from member states to CERN and show alternative ways: a new financial model for FCC, allowing cost sharing between CERN member states in the form of in-kind contributions (in contrast to cash contributions), could raise the willingness to support the construction of a new collider. The basic idea is a "rent-a-research-infrastructure-model" that enables local industry of member states to deliver components needed for FCC instead of the member states' cash contributions. Similar models (of course in a much smaller scale) are already used in applied research for joint large-scale pilots between industry and research. The industry partners deliver components and software to build the infrastructure while the research organisations take care of the daily operation and experiments.

There are good examples in the field of applied research. For example, the 26 testbeds of the Industrial Internet Consortium (IIC) are owned and operated by industry partners. Testbeds provide platforms to think carefully about innovations and test new applications, processes, products, services and business models to make sure they are useful and viable before taking them to market. They uncover the technologies, techniques and opportunities essential to solving these and other important problems that benefit businesses and society. Of course, testbeds cannot be compared to Big Science infrastructure, but the funding and beneficiary approach can certainly be learnt and the appropriate elements can be adopted for future CERN projects. An important criterion for future operating concepts is clearly the trade-off between independent research and industrial dependency.

A.2 Decentralisation of quality control and testing for components

Basic enablers for the success of a multi-tier-supplier-approach are the decentralisation of quality control and international standardisation of all functions and interfaces required for frictionless assembly and faultless operation. For this reason, a concept to encourage delivering nations and their companies has to be developed.

This approach is closely linked to the necessity for a gradual knowledge transfer strategy based on Technology Readiness Level (TRL). This TRL framework could help to identify areas where products and components are directly available on the market (high TRL from 8-9) and no knowledge transfer is needed. Products and components with a medium TRL (TRL from 4-7) could be further developed by lean knowledge transfer and joint development of alternative markets with unified standards, quality control and tests. Products and components with a low TRL (TRL from 1-3) need to be developed following closely coordinated joint development and rapid knowledge transfer to companies.

A.3 Acceleration of knowledge transfer from CERN to industry (suppliers)

Based on the above changes to supplier management, another issue needs to be considered. Industry typically needs some time to implement new manufacturing processes and products. This ramp-up-time is an important factor for the time schedule of assembling the FCC. The time needed can only be reduced by starting close collaboration with industry quite early and to give suppliers faster access to CERN knowledge to allow faster ramp-up of production of needed materials, such as superconducting cables or magnets. A major requirement for this is the consistent implementation of developments into products that enable sustainable business for the manufacturing companies. In the past and still today, technologies developed at CERN were transformed into successful products. Examples include diagnostic devices in medical technology, touch screens and various sensors. However, these are coincidental successes and not strategic developments. Without diminishing the successes from the past, there is significant potential for changing the mind set from having a purely functional focus on the experimental equipment to focusing on the implementation and exploitation of products in industry.

In addition, knowledge transfer from industry into CERN could also bring some benefits. Especially when it is about adopting industrial standards and concepts e.g. for production planning or quality control. Research and transfer partners, like Fraunhofer or others, could build the link between basic research and cutting-edge technology developed by CERN and the market-driven solutions from companies. Particularly in the areas that are not directly connected to physical experiments, further potential can be raised by drawing on experience from other (industrial) areas. Many years of experience are available, for example, in the field of mine ventilation, which can be transferred well to tunnel ventilation. There is no need to reinvent the wheel. In fact, it can be assumed that mature solutions make a significant contribution to increasing efficiency and that development cycles can be skipped. The same applies, for example, to the energy management of large-scale plants. Another starting point for future cooperations and the expansion of CERN's “research service portfolio” is the use of the CERN site as a testbed for electro mobility, smart home, smart maintenance, etc. As a self-contained city in the city, CERN offers an ideal ecosystem with its 10,000 employees and extensive infrastructure (even outside the trials).

Annex B

Table ANNEX-B-1: Number of facilities (coldmass/final test benches, assembly lines) to avoid needing to test magnets before startin with magnet installation (22.11.2035)

Alternative			A1	A2		A3			
Process Test Times Considered	Process	Shaft	A	C	K	C	K	E	I
1x LHC	Assembly (5,33 Days)	# Assembly Lines	35	17	17	9	9	17	14
	Coldmass Test (5 Days)	**# Coldmass Test Benches**	**25**	**12**	**12**	**6**	**6**	**12**	**10**
	Final Test (0,5 Day)	# Final Test Benches	3	2	2	1	1	2	1
2x LHC	Assembly (10,66 Days)	# Assembly Lines	68	33	33	17	17	32	24
	Coldmass Test (10 Days)	**# Coldmass Test Benches**	**49**	**24**	**24**	**12**	**12**	**23**	**17**
	Final Test (1 Day)	# Final Test Benches	5	3	3	2	2	3	2
3x LHC	Assembly (15,99 Days)	# Assembly Lines	101	50	50	25	24	34	25
	Coldmass Test (15 Days)	**# Coldmass Test Benches**	**73**	**36**	**36**	**18**	**17**	**34**	**25**
	Final Test (1,5 Days)	# Final Test Benches	8	4	4	2	2	4	3

Table ANNEX_B-2: Number of Facilities (Coldmass/Final Test Benches, Assembly Lines) to avoid needing to test magnets in advance of starting with magnet installation AND storage of tested magnets before installation (JIT – Assembly and Testing)

Alternative			A1	A2		A3			
Process Test Times Considered	Process	Shaft	A	C	K	C	K	E	I
1x LHC	Assembly (5,33 Days)	# Assembly Lines	59	22	38	22	38	22	22
	Coldmass Test (5 Days)	**# Coldmass Test Benches**	**43**	**16**	**27**	**16**	**27**	**16**	**16**
	Final Test (0,5 Day)	# Final Test Benches	5	2	3	2	3	2	2
2x LHC	Assembly (10,66 Days)	# Assembly Lines	117	45	75	44	75	44	44
	Coldmass Test (10 Days)	**# Coldmass Test Benches**	**85**	**32**	**54**	**32**	**54**	**32**	**32**
	Final Test (1 Day)	# Final Test Benches	9	4	6	4	6	4	4
3x LHC	Assembly (15,99 Days)	# Assembly Lines	176	66	112	65	112	66	66
	Coldmass Test (15 Days)	**# Coldmass Test Benches**	**127**	**48**	**81**	**47**	**81**	**48**	**48**
	Final Test (1,5 Days)	# Final Test Benches	13	5	9	5	9	5	5