COMPUTER AIDED CAPACITY MANAGEMENT LIFE CYCLE SUPPORT FOR TRANSIT SYSTEMS

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ABSTRACT

This paper describes the capacity management life cycle process for transit systems on an abstract level and how this life cycle can currently be supported by computer based systems. It points out four major steps in the life cycle process and shortly sketches how transitioning between them can be realised in an integrated process. Bridging the gaps between these steps is not in all cases an automatically solvable task though same hints and references are given how these cases could be tackled.
Starting from the analysis of transport and traffic flow requirements, called the strategic network planning, the layout of infrastructure is studied in the following. This infrastructure planning process is the basis for infrastructure construction and modification activities, which usually are time and cost intensive. Therefore detailed capacity analysis should be performed to justify layout decisions. As soon as a certain infrastructure layout has been selected and set up, scheduling and train path allocation can be done. With these schedules the real operation can be performed. The operation including rescheduling and dispatching is the last step of the capacity management life cycle.
Additional to the description of the life cycle steps the paper gives a short overview of tools supporting the different activities and which data or data structures are required respectively which approaches exists to establish an integrated computer support for this life cycle.

Keywords: infrastructure life cycle, network planning, model train, data structure, tool support

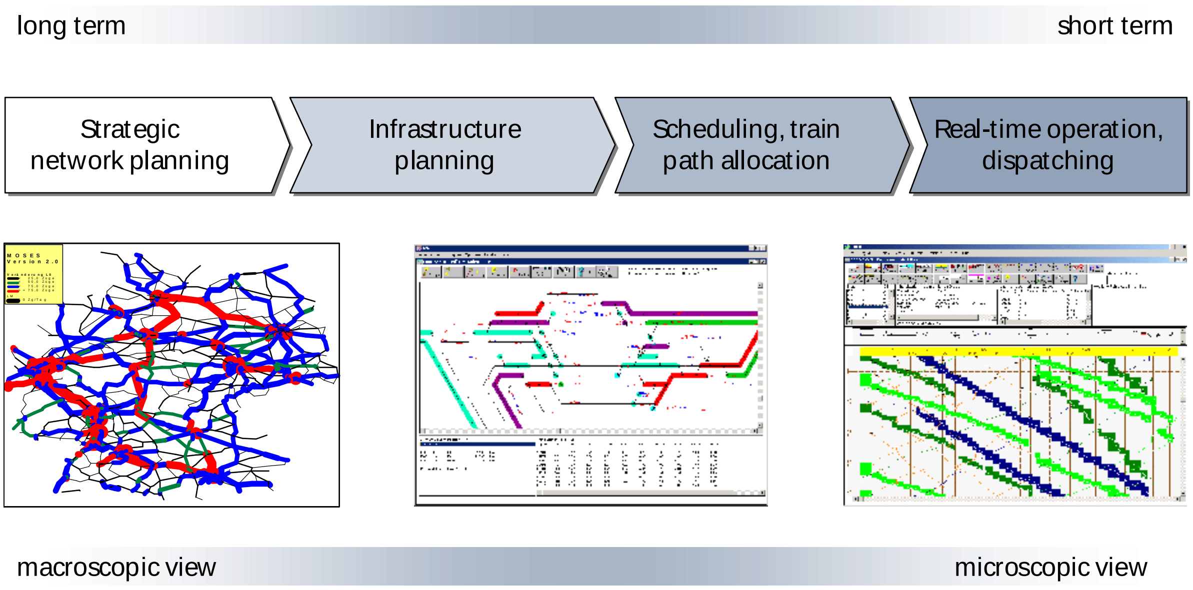

Figure 1 – Life cycle steps of capacity management

INTRODUCTION

In the context of railway operation, capacity management commonly denotes the spatio-temporal allocation of infrastructure resources to a train movement, also called a trajectory. A couple of trajectories finally set up a schedule. This understanding is an unfounded restriction of infrastructure capacity usage to a narrow time horizon. Finally the available and manageable infrastructure capacity is the consequence of long term planning and development.

Roughly speaking, capacity management starts with the evaluation of expected traffic flow and design of model schedules and traffic. With these model schedules, different infrastructure layouts may be evaluated with respect to their operational and economical suitability. Identifying best fitting infrastructure layouts for expected traffic needs far in advance allows reconstruction, rebuilding or restructuring actions, which usually requires a couple of years and high investment costs. According to this the infrastructure and traffic analysis phase is an essential one but commonly unconsidered step within the capacity management process.

The concrete scheduling process - denoted as capacity management (introduced above) - uses the capacity provided by the available infrastructure. As an additional comprehension the real time usage of infrastructure extends the meaning of capacity management. This extended understanding of capacity management can be named as the life cycle of capacity management. A rough overview of this life cycle is given in Figure 1.

Several years, probably decades in advance the strategic network planning evaluates vital statistics, traffic streams and modal splits to determine expected transport capacity values. This phase is usually completely independent from concrete infrastructure or timetables. Nevertheless, in practice existing infrastructure is considered and associated capacities are merged into the macroscopic railway network.

Using characteristic values derived from the strategic planning infrastructure studies and layouts become possible. These activities are performed to set up infrastructure that is sufficient for future traffic streams. At this stage, five to fifteen years in advance, usually the first microscopic infrastructure is considered in the course of layout studies and capacity analysis. Seriously no real timetable data can be provided but analytical information like model trains, number of trains or train distribution are sufficient data granularity to analyse network bottlenecks or robustness of possible timetables for the planned infrastructure etc.

In contrast, real timetable data modelling single train movements are the core information for scheduling and train path allocations. Most current applications dealing with capacity management like railway operation simulation or timetable robustness evaluation cover operations of this phase and use microscopic data structures. This phase usually starts several months before the timetables become valid.

The last phase of capacity management faces the practical railway operation due to timetables and real operational requirements. Dispatching system and computer aided rescheduling are activities to be supported by computer systems at this stage.

Additional phases like billing or bonus malus systems may be added to this life cycle of capacity management but principally no infrastructure is involved in these phases any more and therefore excluded from further considerations within this paper.

In this paper the different phases are explained more precisely and sufficient data structure for the different phases and information derivable or operations applicable are analysed.

Finally this paper evaluates how computer systems currently support these life cycle phases and how data structures and data flow can sufficiently be set up to allow an integrated life cycle support.

LIFE CYCLE OF CAPACITY MANAGEMENT

Strategic Network Planning

The strategic network planning is an important precondition for railway network modifications, extensions or reductions. Changing infrastructure is a long term task implying high costs and investments.

Therefore it is essential to forecast oncoming transportation requirements and traffic streams set up by supply and demand. This strategic planning has different characteristics:

- No real infrastructure layout is required, a very macroscopic approach is sufficient.
- Due to the long term in advance and the long-living infrastructure schedule independent approaches are required.
- Strategic network planning may aim increasing infrastructure capacity, shorter travel times or to increase schedule qualities like timetable robustness or delay reduction.
- Traffic streams must be representable by model trains, which themselves represent the intended transport services.

While the first item corresponds to the infrastructure model requirements of this capacity management step the remaining items face the services to be offered by railway undertakings.

Formally speaking, strategic network planning can be seen as an operations research problem [3] where locations (cities, stations or regions) are given as well as traffic demands between these locations. All traffic demands are transformed into a suitable number of model trains going from location A to location B (via an a priori unknown journey). Additionally we have a cost function telling us incurring costs for a railway connection being realised at a certain stage of expansion between any two locations. Finding an infrastructure which satisfies all traffic demands at minimal costs is now an NP-hard problem. Further on the cost function has to be chosen carefully since all aims of strategic network planning are implicitly contained in it. Roughly speaking, we typically can not have all aims fulfilled at the same time, e.g. given a certain budget one might have to weight travel times versus high connectivity between locations. Nevertheless, a solution of the outlined problem yields a railway infrastructure from which also all concrete model train journeys can be deduced. As it will be mentioned, following steps of the capacity management life cycle need to know a train's concrete journey given by a sequence of locations.

Macroscopic Infrastructure

The strategic network planning requires quite rough infrastructure information. The information can be modelled by graphs $G_a=(N_a, E_a)$ with a set of Nodes N_a representing cities, stations or regions (depending on the granularity of traffic flow consideration) and another set of directed and weighted edges E_a, where e Î E_a, $e=(n_1, n_2, w)$ and n_1, n_2 Î N_a.
An edge e is a directed connection between two graph nodes representing a traffic stream respectively transport service between these nodes. The quantity of this stream or service is given by a weight factor w representing number of travellers, of trains or volume of cargo. Figure 2 shows an example of this macroscopic infrastructure data modelled as a graph.

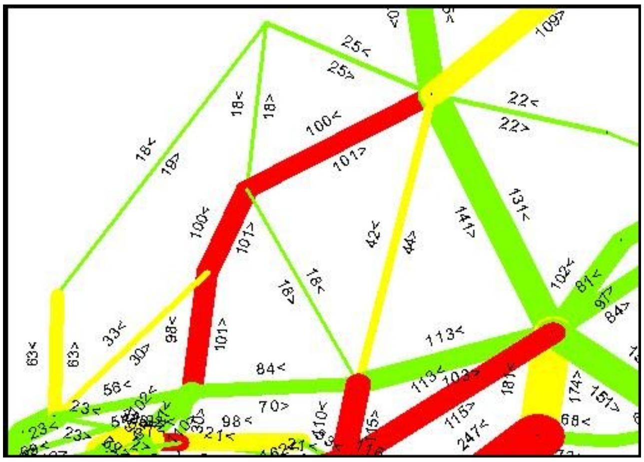

Figure 2 – Macroscopic Infrastructure for Strategic Network Planning

Model Train Data

As mentioned the edges of the strategic network graph are weighted by property values derived from the traffic stream requirements determined.

These weights can represent number of travellers or goods, expected number of trains or other characteristic properties. Typically there is no schedule available yet. The granularity of train modelling may be extended to model train representation. More detailed approaches are not seriously feasible at this capacity management stage.

Infrastructure Planning

The number of trains and passengers leads to the next step, the infrastructure planning. The concrete layout of infrastructure is planned, analysed and evaluated but nevertheless concrete schedules are not seriously possible yet.

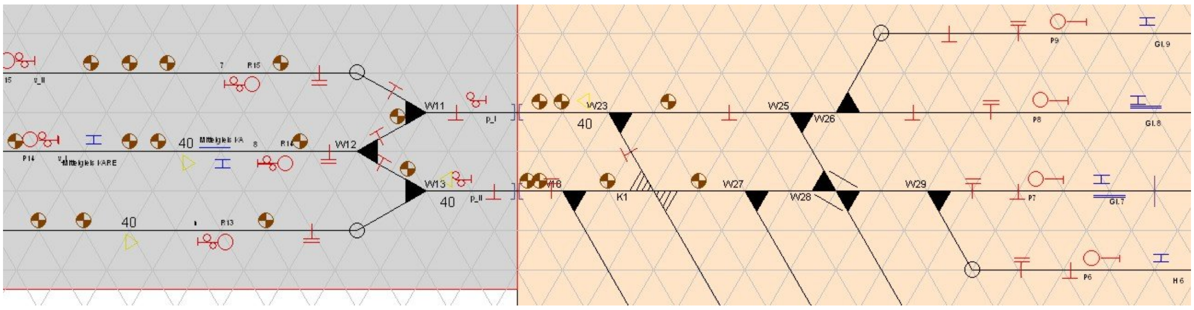

Figure 3 – Microscopic Infrastructure for Infrastructure Planning

Microscopic Infrastructure

As mentioned within the introduction the microscopic infrastructure data is required the first time to perform analysis and evaluation tasks. While the macroscopic infrastructure model of the strategic network planning determines characteristic values like number of trains respectively travellers or goods the infrastructure planning process has to satisfy these capacity requirements. Tasks to be performed with this infrastructure planning process are:

- the elementary study of infrastructure layout variants
- the evaluation of infrastructure planning costs, of modifications required in contrast to current infrastructure
- The evaluation of bottlenecks and capacity of specific layout variants with respect to transport requirements.

To perform these tasks, microscopic infrastructure data must have a granularity down to at least tracks, switches between tracks and intended routing and train protection system devices. While routing functionality includes information about technical feasible routes an interlocking station can establish the train protection system functionality. It also has to provide information about minimum headway times or data to compute it dynamically.

Similar to the macroscopic infrastructure modelling the microscopic infrastructure can be modelled by a directed graph $G_i = (N_i, E_i)$ with a set of Nodes N_i representing infrastructure elements (switches, signals, crossings etc.) and edges E_i representing tracks connecting the infrastructure elements.

Using this graph and considering given model trains the infrastructure capacity analysis can be performed employing analytical approaches like queuing theory or distribution function.

Figure 3 shows an example of microscopic infrastructure for computer based capacity evaluation with queuing theory approaches and clustering of infrastructure.

One specific aspect of the infrastructure model used within this phase is the derivation of G_i from G_a, denoted as $G_a \rightarrow G_i$. The complete new creation of microscopic infrastructure graphs is a time consuming task. Thus a (semi-) automatic derivation of infrastructure graphs from model train information and macroscopic infrastructure would deliver a basis for infrastructure modelling and moreover close the gap between the macroscopic and the microscopic approach.

Model Train Data

As before for the strategic network planning the infrastructure planning process is performed years before a concrete timetable is established. The infrastructure planning process can seriously consider intended train and transport characteristic, like number and kinds of trains or cycle numbers and length but an in-depth constructed timetable with concrete train runs is not suitable at this time due to different reasons:

- The capacity characteristic of microscopic infrastructure combined with concrete timetables is quite fragile with respect to small modifications.
- Analytical approaches with probability distribution functions and queuing models are more general and valid.

Model train data is therefore sufficient for this phase and the recording of model train data can be done much faster due to the reduced data density and amount compared to single train data recording.

Beside the route of a model train throughout the infrastructure graph G_i only several additional information are required to evaluate the infrastructure capacity:

- A rough operation program, e.g. number of trains within a specific time range, cycle time or length or train distribution (stochastically) over a time period.
- Tolerance characteristics like delay or malfunction probability or fixing to derive times determine capacity analysis results.

The result of this infrastructure planning process is an infrastructure layout which fits best to the expected capacity requirements with respect to different target functions like timetable robustness, capacity optimization or economic aspects (e.g. construction and modification costs).

Scheduling, Train Path Allocation

When the infrastructure planning process has been performed and the infrastructure will finally be available as desired, the scheduling process can be carried out. Within the scheduling process model trains are converted into concrete instances of train runs with arrival and departure times, dwell times and headway times respectively blocking times. The computation of concrete infrastructure usage and the consideration of train protection systems is required because the train path allocation has to consider the restrictions which imply the real train operation.

This phase of the capacity management life cycle is usually named as capacity management in a narrow sense. Several tools and computer systems exist to support this phase partially. Due to the requirement for detailed modelling of train operation practice microscopic infrastructure models as well as microscopic train modelling is required.

Microscopic Infrastructure

The basic pre-condition for scheduling and train path allocation is the availability of microscopic infrastructure data.

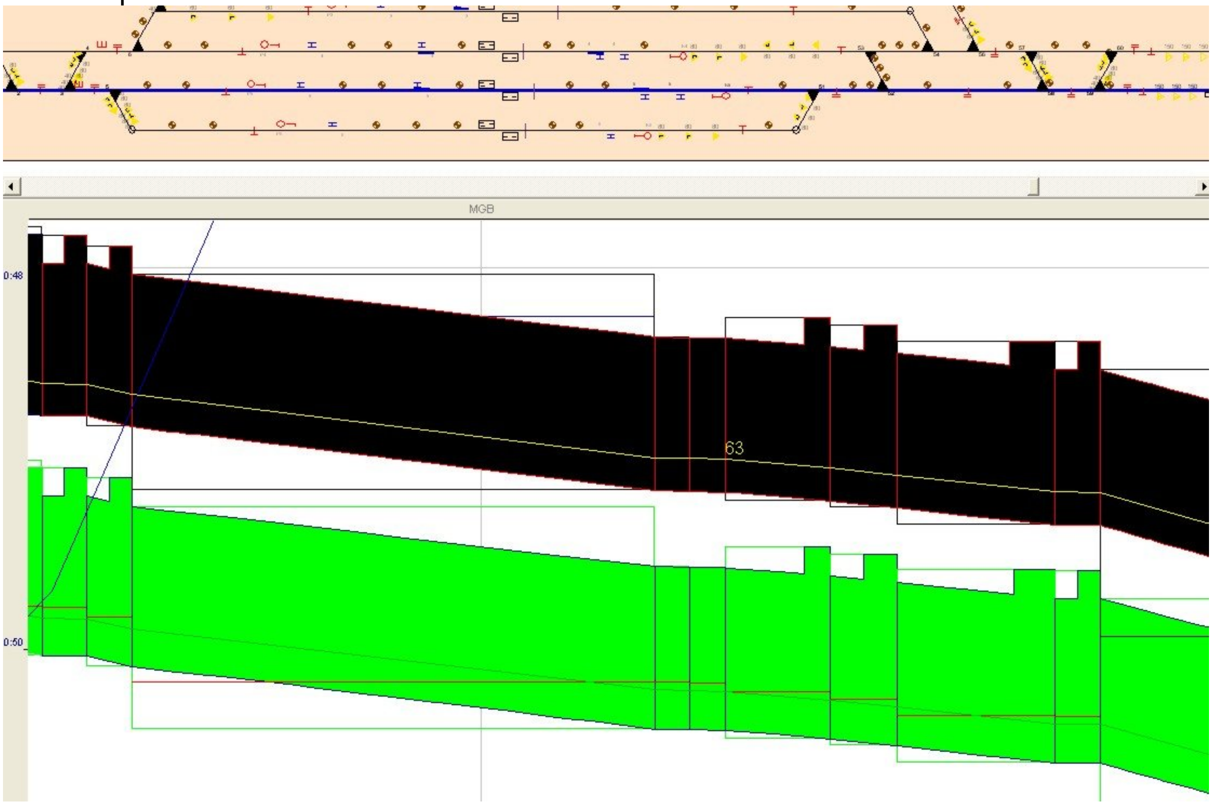

Figure 4 – Association between microscopic Infrastructure and timetable data (e.g. ETCS level 3 study)

Similar to the infrastructure planning phase the scheduling phase requires detailed information about single elements of the infrastructure, which determine blocking times, route exclusions and running times resulting from physical train data and topological information.
Therefore the infrastructure underlying the scheduling process has to fulfil some requirements:

- § Detailed representation of infrastructure topology including switches, crossings and distances.
- § Representation of track characteristics required by the running time computation like gradients, curve radius, tunnel or speed profiles.
- § Information required for blocking time computation like signals, stop positions or axle counters respectively track circuits.

An example for this microscopic representation is shown in Figure 3 and 4.

Microscopic Timetable and Train Paths

The major difference between the data used for infrastructure planning and for scheduling are the train information. While model train information including number of trains or distribution within a day matches the infrastructure planning process in the best way the scheduling process relies on concrete departure or arrival times, dwell times and bordering requirements like margins or operation times, linking connections and days of operation.

Therefore the data required for this last scheduling step before real operation must provide several information in addition to model train data:

- The route of a train throughout the infrastructure graph *G*.
- A detailed operation program including arrival and departure times, stopping times and minimum dwell times.

Similar to the model train computation blocking times can be derived from the underlying train protection system. The blocking times are an essential element to build conflict free schedules. Overlapping blocking times indicates unfeasible schedules.

Figure 4 shows an example of microscopic infrastructure and train runs and their derived blocking times (of an ETCS level 3 study).

Real-Time Operation and Dispatching

After schedules have been set up, the trains may operate as scheduled. Trains should operate and use the infrastructure capacity as it was planned in the schedule. Ideally all trains operate as defined but in reality disturbances are always implied, resulting in train runs which do not match the scheduled times.

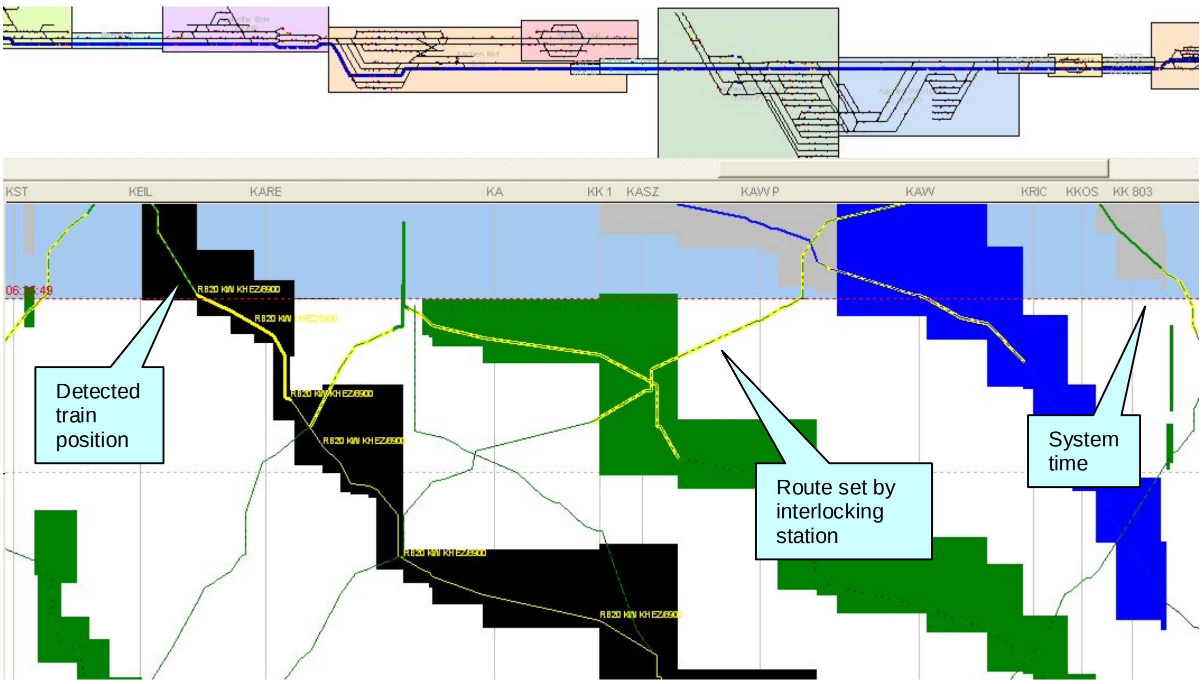

Figure 5 – Real-time train position and route detection for dispatching and rescheduling.

With these modified travel times train protection systems produce new blocking times. As long as blocking times do not overlap, no side effects will occur, but as soon as blocking time conflicts occur, trains can not operated as scheduled any more because train protection systems will prohibit signals to switch to a proceed aspect.

Usually rescheduling and dispatching activities are required in this situation to ensure a high infrastructure capacity usage; therefore this phase is included in the capacity management life cycle.

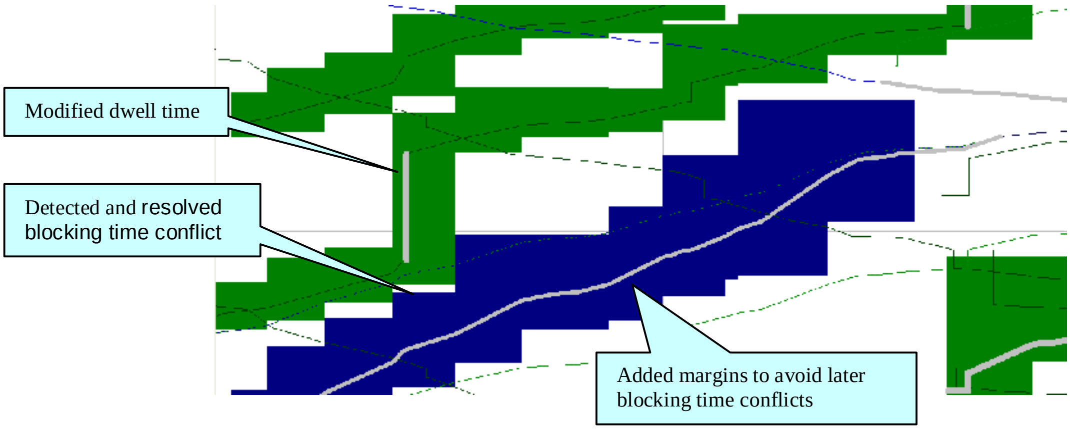

Figure 6 – Rescheduled train runs with modified margins and dwell times (thick gray lines)

Supporting computer systems must be connected to operational systems, detecting train positions and route settings as shown in Figure 5. With these information infrastructure capacity usage conflicts can be evaluated, train runs can be rescheduled and real-time dispatching can be established (Figure 6).

This life cycle phase requires the same data structures as the scheduling process. Microscopic infrastructure data is required, because position detection as well as train run computation relies on detailed infrastructure information, the train data must have the same granularity as for scheduling to perform the same computations in real-time.

COMPUTER AIDED SUPPORT

While the last chapter roughly outlined four phases of capacity management life cycle this chapter analyses the support computer systems may provide. As introduced, different data structures are required within the different life cycle phases. Implied by the data structure varying algorithms and approaches are possible. This is reflected by different tools and existing computer systems. Both aspects are described in the following subsections. Finally the integration of the different life cycle phases of capacity management is described in the third subsection.

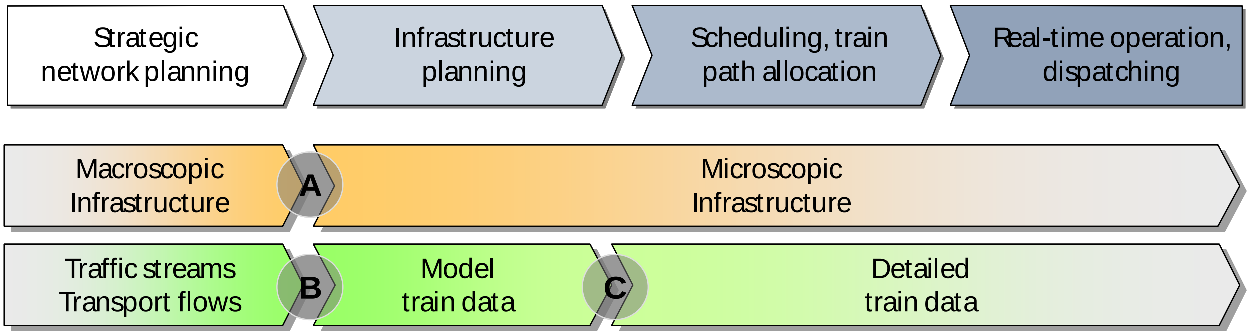

Figure 7 – Major Lifecycle steps and transformation requirements

Data Structures

Figure 7 sketches which kind of data is processed in which step of the capacity management lifecycle. A short summary of the required data structures is given in the following:

- § The macroscopic infrastructure for strategic network planning is usually represented by (directed) graphs, where graph nodes represent locations like cities or stations.
- § The microscopic infrastructure is also represented by directed graphs. The graph nodes represent infrastructure elements like switches, signals, gradients, stopping positions, curves, tunnels, mileage changes, crossings, axle counters etc.
- § The transport stream information are rather abstract characteristics, from which transport necessities may be derived, e.g. number of persons expected for a relationship, tonnage of cargo between two macroscopic nodes etc.
- § Model train data contain detailed physical information about a class of trains, e.g. the traction and the braking ability, a path for trains of this class throughout the microscopic infrastructure and abstract information about the number of trains of this class, e.g. numbers of trains within a time period, running density throughout a day etc.

Especially the real-time operation can not be limited to the presented system internal data structures any more. In addition to the data structure listed above dispatching systems must be able to process data of the operating system; therefore systems supporting this last phase of capacity management can not be autonomous any more. Nevertheless, information flow between the microscopic and the macroscopic level is possible in both directions. Any microscopic infrastructure and its capacity constrains can be aggregated to a macroscopic model, while model trains (and their routes) can be migrated to the microscopic level. In case that it is necessary to build a new or expand an existing railway connection there are also proposals how to create microscopic infrastructure in a standardized (and thus automatable) way ([2], [4]).

Tools

Different tools exist, focussing single aspects of the capacity management life cycle. But as far as known by the authors there are no overall solutions covering all aspects. This is not surprising due to the different data structures, processes and application fields, but for single aspects the tools are more or less powerful and applicable.

Strategic network planning

For strategic network planning different approaches and tools exists. While different tools like MOSES or WIZUG [5] face very special aspects of network planning Netvisio [6] allows the definition and visualisation of network properties and network layouts. The approach of MakSi-FS focuses on macroscopic simulation of timetable concept robustness and punctuality. Additionally, a wide range of introducing (scientific) literature about transport flow was published by Gerhardt Potthoff [1].

Infrastructure planning

In contrast to tools for strategic network planning the number of tools sufficient for infrastructure planning is larger. Nevertheless most tools like OpenTrack [7], RailSys [8] and much more use a more or less microscopic infrastructure model and derived blocking times or minimum headway times, but the usage of timetable independent (stochastical) model train data is not possible. These tools simulate the operation of one specific timetable; all results are valid for the one timetable version. Due to the time the infrastructure planning is done in advance of a concrete timetable a huge amount of possible timetable variants is required to obtain serious result. This makes these approaches very time and cost extensive.
In contrast analytical approaches like ANKE [10], STRELE [10] or LUKS [11] using model train data deliver simulation results which can be used for infrastructure analysis independently from a concrete timetable.

Scheduling and train path allocation

Most railway companies use computer aided timetabling tools nowadays. Some examples are FBS[9], the system RUT-K (used by DB Netz AG in German), TPS [12], Faktus/RUT-0 [10] or the construction modules of LUKS [11].
Tools differ in the size of manageable infrastructure and timetable data, performance, system complexity, pricing, implemented country specific characteristics, user interaction, interfaces and supplied visualisation and output functionalities.
Additionally other tools using more abstract infrastructure like VIRIATO [6] exist, which allow a strategically oriented analysis and design of schedules and their visualisation.

Real-time operation

Finally operation control centres for centralized real-time operation coordination became more important for several railways in the last years. The systems implemented there are usually security relevant systems and bound to country specific techniques, rules and vendors.
These systems offer more or less powerful rescheduling and dispatching support functionality, but real-time automatic dispatching is still an active field of research and development activities.

Some ongoing research activities which might result in productive tools are the algorithm centred ROMA [13] and ASDIS [10] systems or the overall system and architecture oriented project DisKon in Germany [14] using the UIC-broker interface [16].

Integration and Vision

After identifying different data structures and tools for the capacity life cycle phases the integration of the different phases into one coherent process appears to be possible. The stages infrastructure planning, scheduling and real time dispatching all belong to the microscopic level and thus use common data structures. These are basically directed graphs having the same resolution of infrastructure details as well as common data structures for representing (model) trains. Among these three microscopic levels train data differ mainly in the nature of their respective schedules: While infrastructure planning is performed without concrete timetables at all during the scheduling phase time tables are created by definition, which then make up the basis for real time operation.
On the other hand strategic network planning is accomplished on the macroscopic level where all information is aggregated to a higher level of abstraction. Thus in the transformation from microscopic to macroscopic level (denoted G_i ***à*** G_a) detail information gets lost. It has to be (re-)provided when performing the reversal transformation G_a ***à*** G_i.

A: From macroscopic to microscopic infrastructure data

Up to our knowledge, there are no published standardized and accepted ways to automatically enhance existing microscopic infrastructure (or to build microscopic infrastructure completely from the scratch) which fulfils capacity demands coming from the macroscopic level. So, from a computer scientist's point of view, the transformation G_a ***à*** G_i remains a gap in the capacity management life cycle.
In practice, there are many restrictions on railroad lines imposed by the surrounding geography. Nevertheless, [2] describes ways to design railway centres in a standardized way, while [4] examines optimal block arrangements. These scientific approaches might be sufficient for oncoming tools to offer semi-automated microscopic infrastructure layout.

B: Defining model trains from traffic streams

The definition of model trains is usually done on the macroscopic level. Different approaches exist to map traffic stream and transport flow characteristic values to means of transport. The way how model trains can be defined also depends on the nature and existence of constraints to adhere to.
In case that network capacity can be neglected a single traffic stream from point A to point B can easily be mapped to an appropriate set of model trains. Given train capacities C and traffic volume V the minimal necessary number of model trains N serving this demand is given by $N = V/C$. Further on, each model train will have a shortest possible route.
On the other hand, given a railway network with finite capacity, a list of model trains (defined by their respective starting and ending location) and a simple cost function counting the

number of served trains finding an optimal solution is an NP-hard problem. In practice there are many more demands on model trains. Among these are short running times, adherence to a cyclic schedule, predetermined journeys and a limited number of rolling stock. Furthermore, overlapping traffic demands should not be served by distinct trains whenever possible. Though finding an optimal sample of model trains seems to be out of reach we yet do not have to interrupt the computer aided workflow here. A sample fulfilling traffic demands at least partially can still be generated by a computer (e.g. using heuristics). Resulting model trains are implicitly characterized in terms of their journey, capacity and a probability-distribution of their frequency.
A concrete heuristic (described in [15]) realises the unrestricted approach described above. Traffic demands are determined separately for each relation where it is assumed that passengers always use shortest routes. The overall number F of passengers using a single edge is summed up for each edge. The number of trains necessary to cross this edge is then calculated from F, from train capacity and from an average degree of utilization per train.

C: Deriving train data from model trains

Probably the easiest step in the capacity management life cycle is the creation of tangible trains based on model trains. Since the journey of a model train is known there is only to decide, which concrete routes and times should be taken.
Further on, given the overall number and the probability distribution of how many trains per time unit are to be scheduled, a corresponding sample of trains can be generated. This train instance derivation from model train data is implemented e.g. within the LUKS systems [11] and is used to generate data for further simulation based analysis.

CONCLUSION

This paper outlined the capacity management life cycle for railway infrastructure and current data models, tools and supporting applications. The different data structures needed for the four identified life cycle phases were described as well as approaches to reuse and transfer data from one phase to another. A rough overview of existing tools and standards was given as well as a vision how the life cycle management could be integrated in the future.
As it has been pointed out the transformation from macroscopic to microscopic infrastructure can not be seriously done without procuring additional information. Nevertheless, examinations usually carried out on a handmade microscopic infrastructure might still be reasonably answered using an infrastructure that has been automatically derived from macroscopic infrastructure in a standardized way. Appropriate comparisons might be a field for future research.
Finally it can be stated that all identified phases of capacity management life cycle can be supported by computer systems, that approaches and models exist and that an overall integration of data and workflow seams to be possible. Nevertheless, interfacing components or integrating tools and solutions still have to be developed further and infrastructure companies have to decide about their needs and their system architecture carefully. With

decisions considering sustainable data usage and the integration of existing tools capacity management processes can be made more valuable, more powerful and efficient.

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