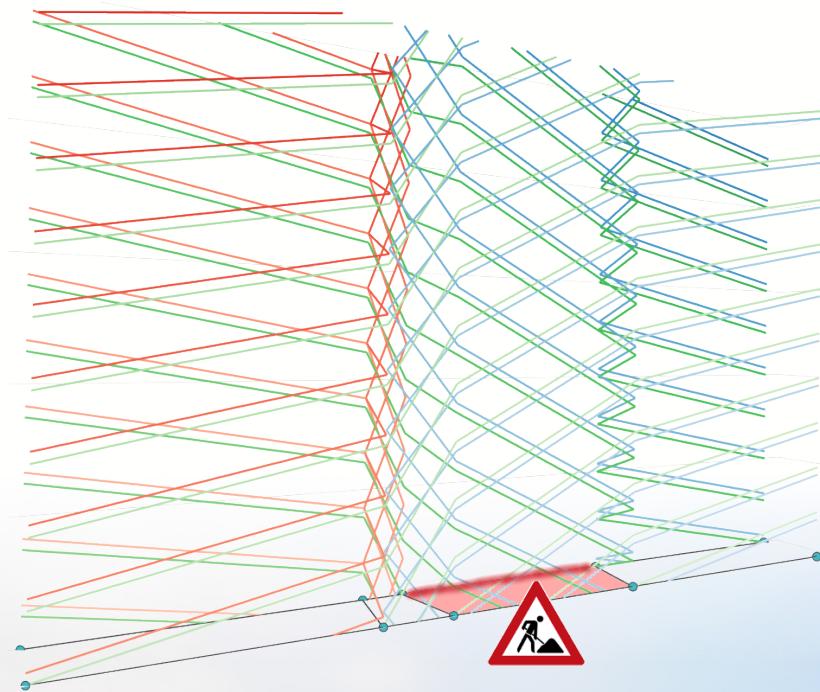


BAUFAHRPLANUNG MIT MATHEMATISCHER OPTIMIERUNG



PROJEKTPARTNER

Dr. Niels Lindner, Berenike Masing



Das **Zuse-Institut Berlin** ist ein interdisziplinäres Forschungsinstitut für angewandte Mathematik und datenintensives High-Performance-Computing. Die Forschung konzentriert sich auf die Modellierung, Simulation und Optimierung in Zusammenarbeit mit wissenschaftlichen Kooperationspartnern aus Wissenschaft und Wirtschaft. Niels Lindner leitet am Zuse-Institut Berlin die Arbeitsgruppe „MobilityLab“, der auch Berenike Masing angehört.

Berlin Mathematics Research Center



Das DFG-Exzellenzcluster **MATH+** ist ein institutionenübergreifender und interdisziplinärer Forschungsverbund. Unter dem Motto „Transforming the world through mathematics“ werden neuartige Forschungsansätze für anwendungsorientierte Mathematik konzipiert und weiterentwickelt. Berenike Masing und Niels Lindner arbeiten im Rahmen des MATH+-Forschungsprojekts „The Tropical Geometry of Periodic Timetables“ an neuen Algorithmen zur Optimierung von Taktfahrplänen im öffentlichen Verkehr.

Prof. Dr. Christian Liebchen



Die **Technische Hochschule Wildau** liegt vor den Toren Berlins, steht in ingenieurwissenschaftlicher Tradition und hat digitale Integration als Querschnittsthema auserkoren. Christian Liebchen wurde an der Technischen Universität Berlin über mathematische Taktfahrplanoptimierung promoviert und ist Professor für Verkehrsbetriebsführung an der TH Wildau.

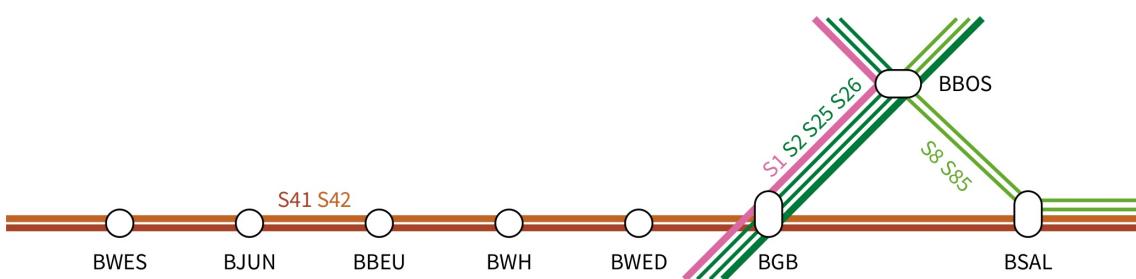


Jens Brandenburger, Colin Peter,
Annette Schön, Björn Stübner

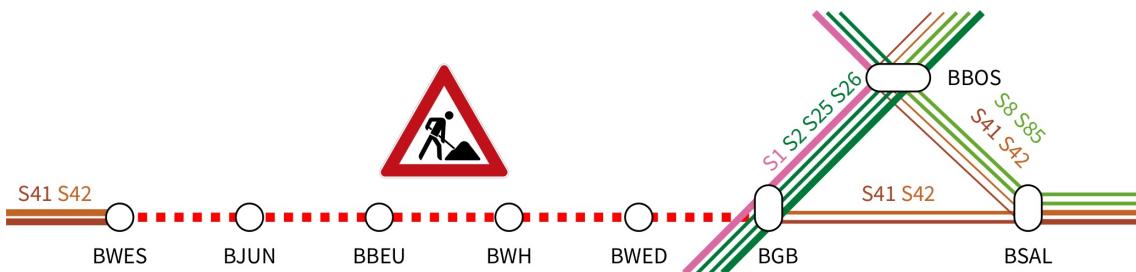
Das Team „Fahrplan und Kapazitätsmanagement S-Bahn Berlin“ innerhalb der **DB Netz AG** erstellt Jahres- und Baufahrpläne für das weitgehend autarke Netz der S-Bahn Berlin. Dies erfolgt in enger Zusammenarbeit mit der Betreiberin S-Bahn Berlin GmbH und dem Verkehrsverbund Berlin-Brandenburg als Aufgabenträger.

HERAUSFORDERUNG

Rund 1,18 Milliarden Euro stellen Bund, Länder und Deutsche Bahn AG im Jahr 2021 für die Modernisierung, Instandhaltung und Erweiterung der Eisenbahninfrastruktur in der Region Berlin-Brandenburg bereit. Auf das Netz der S-Bahn Berlin entfallen dabei weit über 1000 einzelne Baumaßnahmen. Die kleinsten wirken sich nur als Fahrplanabweichungen um wenige Minuten bei einzelnen Fahrten in der Nacht aus, die größeren führen zu mehrmonatigen Sperrungen mit erheblichen Einschränkungen für die Fahrgäste.



Für jede Baumaßnahme auf dem Netz der S-Bahn Berlin müssen seitens des Infraukturbetreibers DB Netz AG angepasste Linienkonzepte und Fahrpläne konstruiert werden. Auf Seiten des Eisenbahnverkehrsunternehmens S-Bahn Berlin GmbH müssen Fahrzeug- und Personaleinsatz umgeplant werden.



Die Anforderungen an ein solches Baukonzept sind mannigfaltig:

Im Sinne der Fahrgäste soll das Regelangebot so weit wie möglich aufrecht erhalten werden. Reiseketten sollen sichergestellt und Schienenersatzverkehr weitestgehend vermieden werden.

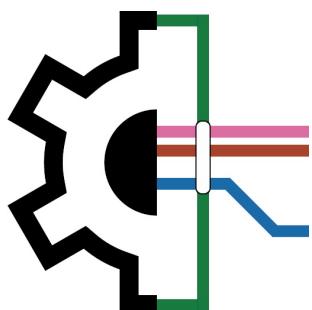
Dementgegen stehen betriebliche Anforderungen, die auf durch Baustellen eingeschränkter oder anders als im Regelbetrieb genutzter Infrastruktur ein gewisses Maß an Stabilität und Handhabbarkeit gewährleisten sollen.

Außerdem müssen tarifliche Regelungen wie z. B. Mindestwendezzeiten oder im Verkehrsvertrag festgeschriebene Mindestzuglängen eingehalten werden. Nicht zuletzt soll ein Baukonzept im Sinne der Fahrgästinformation einfach zu kommunizieren sein.

ZIELE

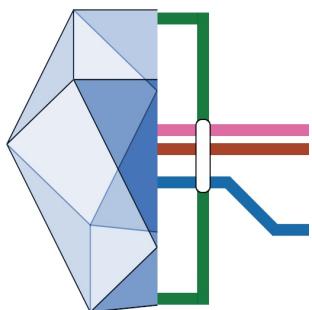
Trotz der großen Zahl an Maßnahmen erfolgt die Planung von Konzepten für den Baustellenverkehr größtenteils manuell. Obwohl Bauarbeiten alltäglich sind, ist dies alles andere als Routine, denn die Anforderungen sind zahlreich und die Planung dadurch äußerst komplex.

Unsere Projektziele sind daher:



Automatisierung

- › Digitalisierung und Beschleunigung des Planungsprozesses
- › Entwurf von Baukonzepten durch maßgeschneiderte datengetriebene Algorithmen



Optimierung

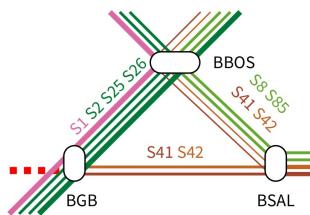
- › Minimierung der Abweichung vom Regelangebot
- › Maximierung des Fahrgastnutzens
- › Einhaltung betrieblicher und vertraglicher Bedingungen
- › Anwendung von Methoden der mathematischen Optimierung

„Im Netz der Berliner S-Bahn gibt es jährlich tausende Infrastrukturmaßnahmen für die Instandhaltung und für den Ausbau der Anlagen. Eine besondere Herausforderung ist dabei, die Auswirkungen auf den Fahrplan so gering wie möglich zu halten, um den Fahrgästen trotzdem ein attraktives Angebot anzubieten.“

Mit der mathematischen Optimierung von Baufahrplänen erwarten wir, dass in der Zukunft die Prozesse zur Lösungsfindung beschleunigt werden, wir schneller auf Änderungen reagieren können und dem Fahrgast rechtzeitig angezeigt wird, womit er rechnen kann.“

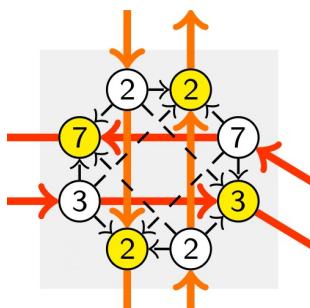
Annette Schön, DB Netz AG, Teamleiterin tagesaktueller Fahrplan für die S-Bahn Berlin

BAUSTEINE



Integrierte Linien- und Umlaufplanung

- › dynamisches Erzeugen von möglichen Linien, Taktfrequenzen und Umläufen auf dem Streckennetz der Berliner S-Bahn
- › inklusive verkürzter Linienführungen, Umleitungen, Pendelverkehren, Schienenersatzverkehren und Linienkopplungen
- › Bewertung von Linien bzgl. Ähnlichkeit zu den Regellinien, Fahrgastnutzen, Fahrzeugbedarf und Infrastruktturnutzung
- › Einhaltung von Strecken- und Wendekapazitäten
- › mathematische Optimierung durch gemischt-ganzzahlige Programmierung (MIP) und Spaltenerzeugungsverfahren

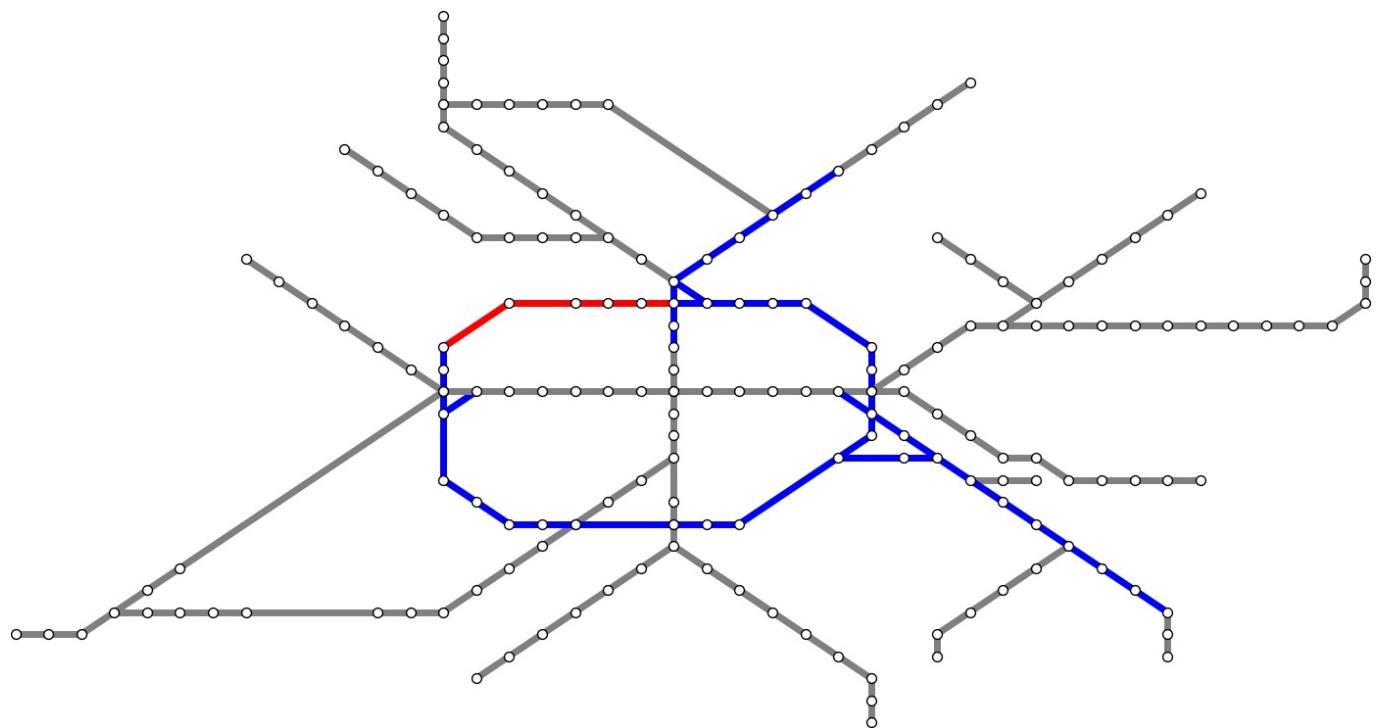


Fahrplanung

- › Berechnen von konfliktfreien Zugfolgetabellen für potenzielle Linienkonzepte
- › Auflösung von Zehntelminuten
- › mathematische Optimierung von Fahr-, Umsteige- und Wendezügen unter Berücksichtigung von Reiseketten und Mindestzugfolgezeiten
- › Einbindung des am Zuse-Institut Berlin entwickelten parallelen Frameworks „ConcurrentPESP“ für Taktfahrplanoptimierung

„Fahrplanoptimierung für den Jahresfahrplan ist das Eine. Die viel häufiger von Planern zu lösende Aufgabe besteht in der Umfahrung baubedingter Einschränkungen, die mitunter nur für wenige Stunden Anwendung finden und vergleichsweise kurzfristig anfallen. Auch in diesem Kontext sollen passende mathematische Verfahren künftig Nutzen stiften.“

PLANUNGSGRAPH



Der **Planungsgraph** dient als graphentheoretische Grundlage für die integrierte Linien- und Umlaufplanung. Er unterteilt das Streckennetz in 3 Bestandteile:

roter Bereich

- › gesperrte Strecken
- › kein Zugverkehr möglich

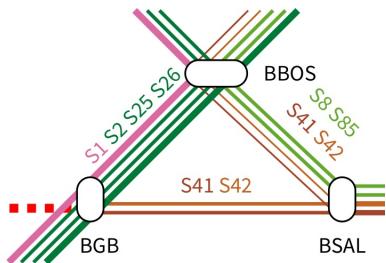
blauer Bereich

- › an den roten Bereich unmittelbar angrenzender Bereich
- › Linienführungen und Fahrpläne dürfen hier verändert werden
- › neue Linien dürfen hinzugefügt werden (z. B. Pendelverkehr)

grauer Bereich

- › außerhalb des roten und blauen Bereichs
- › Linienführungen und Fahrpläne unverändert wie im Regelfahrplan

MATHEMATIK

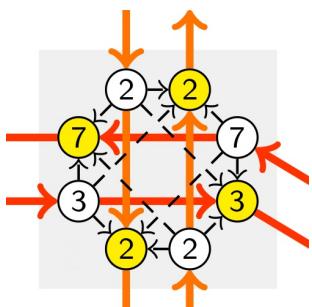
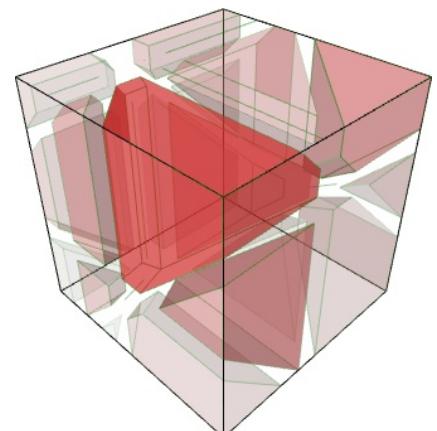
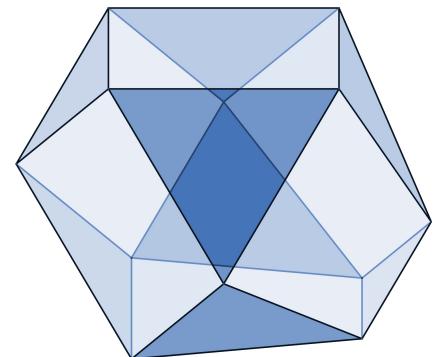


Minimiere $\sum_{\ell \in \mathcal{L}} \alpha_\ell f_\ell + \sum_{\ell \in \mathcal{L}} \beta_\ell x_\ell + \sum_{e \in E} \sum_{\ell \in \mathcal{L}_e} \gamma_e x_\ell$
 sodass $\underline{f}_e \leq \sum_{l \in \mathcal{L}_e} f_l \leq \bar{f}_e, \quad e \in E,$
 $\sum_{v \in V} \sum_{l \in \mathcal{L}_v} f_l \leq \bar{k}_v, \quad v \in V,$
 $x_\ell \leq f_\ell, \quad l \in \mathcal{L},$
 $f_\ell \in \mathbb{N}_0, \quad l \in \mathcal{L},$
 $x_\ell \in \{0, 1\}, \quad l \in \mathcal{L}.$

„Mathematik ist eine Schlüsseltechnologie, die Planungsprobleme im öffentlichen Verkehr elegant modellieren und auf das Wesentliche reduzieren kann. So sind z. B. Umlauf- und Dienstplanung heutzutage ohne fortgeschrittene Algorithmen der diskreten Optimierung undenkbar. Denn mathematische Methoden eröffnen ein Optimierungspotenzial, das ohne sie nicht erschlossen werden kann.“

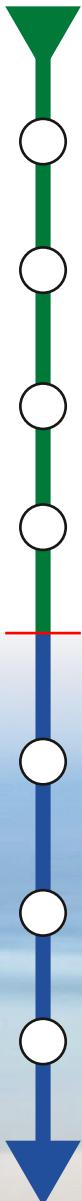
Dr. Niels Lindner, MobilityLab, Zuse-Institut Berlin

Grafiken (von oben rechts im Uhrzeigersinn):
 Ganzzahliges lineares Programm für die Linienplanung,
 3D-Fahrzeitpolyeder, Zerlegung des Fahrplanraums in 3D-Polytropen, gemischt-ganzzahliges Programm für Taktfahrplanoptimierung



Minimiere $\sum_{ij \in A} w_{ij} x_{ij}$
 sodass $\pi_j - \pi_i = x_{ij} - T p_{ij}, \quad ij \in A,$
 $\ell_{ij} \leq x_{ij} \leq u_{ij}, \quad ij \in A,$
 $\pi_i \in [0, T], \quad i \in V,$
 $p_{ij} \in \mathbb{Z}, \quad ij \in A.$

MEILENSTEINE



Digitalisierung und Analyse der Daten
Streckennetz, mikroskopische Infrastruktur, Regelfahrplan

Aufstellung der mathematischen Modelle
für integrierte Linien- und Umlaufplanung, sowie Fahrplanung

Erzeugung des Linienpools
Generieren von sinnvollen Linien und Umläufen

Bewertung des Linienpools
Festlegen von Bewertungskriterien und -maßen für Linien

heute

Lösen der mathematischen Modelle
mit Methoden der gemischt-ganzzahligen Programmierung
bzw. des Frameworks „ConcurrentPESP“

Plausibilitätsüberprüfung
durch die Planer:innen von DB Netz AG

Fertigstellung eines Prototyps
zur automatisierten Erstellung und Optimierung von Baukonzepten



BILDNACHWEISE

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