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Systemic efficiency and capacity: A vital combination in the design of dedicated rail freight projects in Southern Africa

F J Mülke, J H Havenga, J van Eeden

A model was composed that integrated demand for railway services, systemic capacity design of production factors, operating efficiency, and the financial viability of the designed railway operations of a dedicated rail freight project. The design model incorporated efficiency measures essential to successfully developing new railway systems.

The investment in rail infrastructure concerning the geometric parameters and their effect on the project's viability was deduced. A relationship between the geometric layout of track alignment and the hauling process of freight was determined. Results from simulation work to ascertain the operating efficiency informed the design of train-crossing capacity. The effect of inefficiencies on the performance of the production factors and the influence thereof on the rail tariff and the internal rate of return was determined.

The design model covered the range of demand from low volumes of dedicated freight to the advent of heavy-haul operations, and will find its application in cases of new green-field projects. The design parameters applied in sub-models were correlated with the results of field tests and individual new railway projects undertaken in Southern Africa. The results of the effect of systemic operating efficiency on the capacity of the rolling stock fleet were illustrated.

Keywords: demand, capacity, systemic operating efficiency, tariff rate, internal rate of return

INTRODUCTION

Of late, mining ventures have been developing new projects in Southern Africa, and opted to construct and operate their privately owned rail logistics supply chain, linking their mines in the hinterland with a port. Embarking upon these pit-to-port projects emphasised the need to develop a model to design, integrate and optimise the production factors of rail service. In response to this need, a design model was developed to incorporate the design and capacity creation of capital-intensive production factors, the systemic operating efficiency, and the associated returns to scale of a dedicated rail freight system.

This paper attempts to explain the development of an integrating design model that will correlate the production factors' effective and productive capacity design with the efficient performance level of the systemic operations driven by demand. The systemic operating efficiency is expressed in terms of the actual cycle time, also referred to as the turnaround time (TAT) of a railway system and termed as a factor of the most time-saving TAT. An essential feature of the design model entailed the simulated effect of systemic operating efficiency on the capacity deployment of the rolling stock and the integration with the rail infrastructure alignment.

The sub-models determined the capex and opex of the design of the production factors. These were integrated into the financial model to produce the project's final rail tariff rate and internal rate of return (IRR).

Finally, applying a dashboard of the design model produces financial results that will ensure a closer valuation of a railway project to its final value at an early phase of its development.
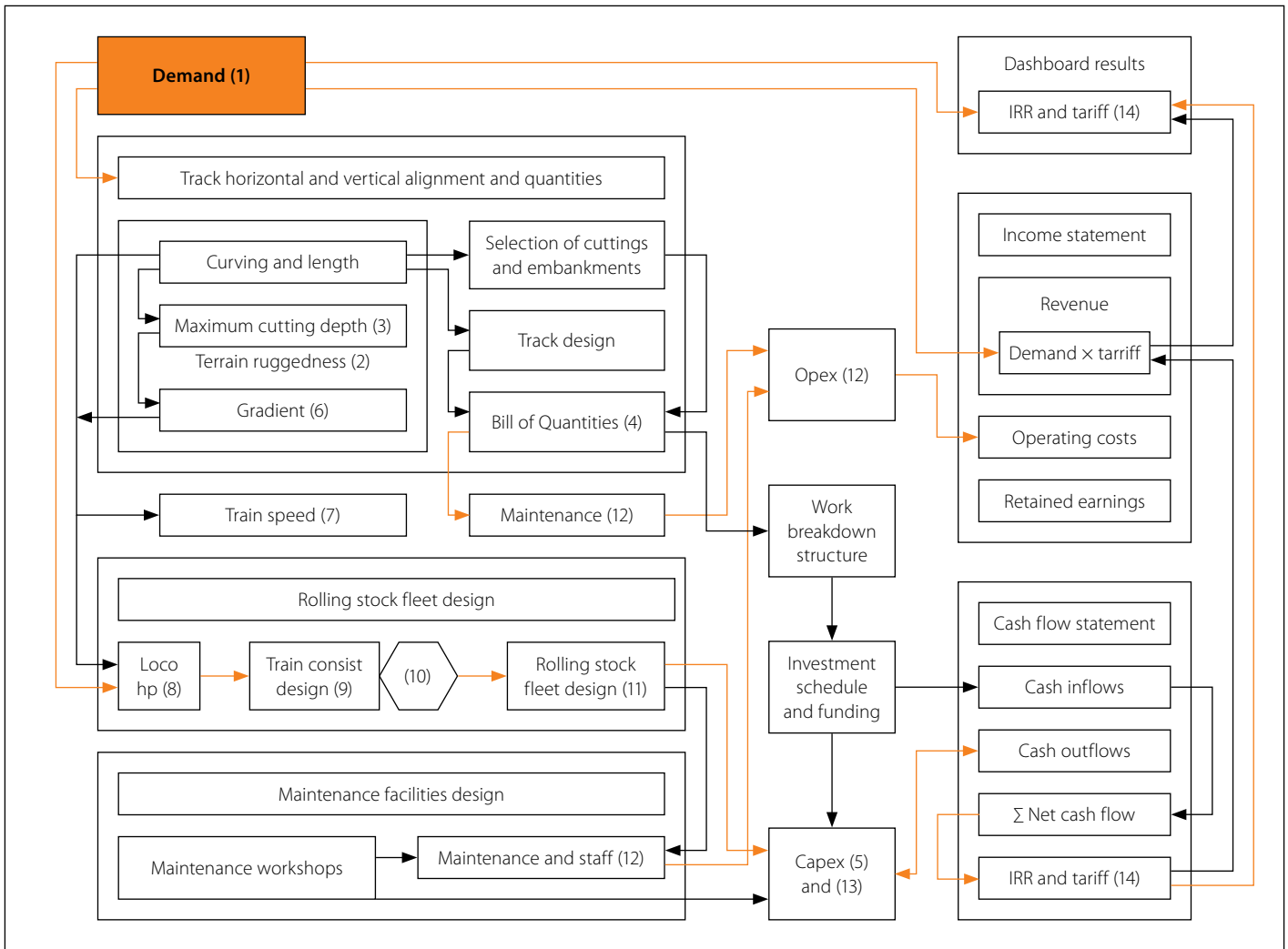
Figure 1 The interrelatedness between the demand, production factors and financial viability

OBJECTIVES OF THE RESEARCH

The primary objective of this paper is to give an exposition of the development of an integrating design model that will correlate the effective and productive capacity design of the production factors with the efficient performance level of the systemic operations driven by the demand depicted in mega tonnes per annum (Mtpa), for a new greenfield dedicated rail-freight project.

Sub-objectives of the development of a design model

Achieving the primary objective required the attainment of the following sub-objectives:

■ Sub-objective 1: Establish the interrelationship between the macro geometric layout of the linear track structure and the earthworks volumes.
■ Sub-objective 2: Determine the correlation of the haulage performance of the rolling stock related to the macro geometric track alignment and the demand.
■ Sub-objective 3: Determine the effect of levels of systemic operating efficiency on the capacity of the rolling stock.

■ Sub-objective 4: Determine the effect of the capacities and processes on the capex and opex, the rail tariff rate and the IRR of a new dedicated rail freight project (Kay 1976; Drury 2009).

METHOD OF DEVELOPING THE SUB-MODELS INTEGRATED INTO THE DESIGN MODEL

The approach to developing the integration process of the sub-models into the design model and the analysis of the interrelatedness of the production factors of a new railway system are shown in Figure 1.

The linkages indicate the interrelatedness produced by the demand as the primary driver of the design algorithm (Leonard 1986).

Realising sub-objective 1 (the establishment of the interrelationship between the macro geometric layout of the linear track structure and earthworks volumes) entailed:

■ Determining the demand (1) as the independent variable that drives the selection of variables in the design processes.
■ Observing the undulating topography (2) determines the selection of the

conceptual maximum depth of the cuttings (3) and the minimum radius of the curving of the trackwork, thereby dictating the resultant earthworks cost.

■ Structuring the Bill of Quantities (4) based on the cutting depths, length and number of cuttings and the rail route length, defining the extent of the earthworks capex (5).
■ Determining the macro geometrics of the line, length and steepest gradient (ruling grade) (6).

Pursuing sub-objective 2 (the correlation of the haulage performance of the rolling stock related to the macro geometric track alignment and the demand) was determined as follows:

The demand is a moderating variable for the train consist design. In conjunction with the ruling grade (6) and the summit balancing speed (7), it informed the solving of the number of locomotives with specific power characteristics (8) to haul the train consist (9). The power of the selected locomotive type is a dependent variable interrelated to the demand.

Reaching sub-objective 3 (the effect of levels of systemic operating efficiency on the capacity of the rolling stock) was determined as follows:

- The systemic operating efficiency factor (10) is a moderating variable in determining the rolling stock fleet size.
- The demand is divided by the train consist's payload (9) to solve the required fleet size of locomotives and wagons (11).
- The required rolling stock fleet size (11) determines the capex of the haulage operations and support processes. Its performance on the macro geometrical track layout determines the opex, of which the fuel consumption forms the major cost element.

Attaining sub-objective 4 (the effect of the capacities and processes on the capex and opex, the rail tariff rate and the IRR (Kay 1976) of a new dedicated rail freight project) was integrated into the design model, namely:

- The maintenance of the trackwork (12) and rolling stock (12), including the operational costs for fuel, lubricants, and train crews (12), produced the opex of the railway system (Parajuli 2005).
- The investment in the rail infrastructure, the rolling stock fleet, and the ancillary facilities, e.g. maintenance workshops, informed the capex (13) in the cash flow analysis.
- The revenue of the operations was calculated using the product of the demand and the rail tariff rate. The rail tariff rate controls the IRR (14) and is determined in an iterative method by the opex of the production factors and the demand (1) to produce positive net cash flow.

CAPACITIES OF A RAILWAY SYSTEM

The UIC (International Union of Railways) (UIC 2015) stated that, *"A unique true definition of capacity is impossible. Rail infrastructure capacity depends on the way it is utilised"*, after which Sameni (2012) remarked that capacity *"… is a trade-off between the number of trains, heterogeneity, and average speed"*. The capacity design of a new railway project primarily entails determining the conveyance capabilities of the production factors linked to demand (Sameni 2012).

The selection of capacities (Abril *et al* 2007; Boysen 2012a; Lindfeldt 2015) of the railway systemic sub-systems that had been integrated at haulage performance levels of the demand is shown in Table 1.

THE MACRO GEOMETRIC LAYOUT OF THE LINEAR TRACK STRUCTURE RELATED TO EARTHWORK VOLUMES

The selection of the macro geometrics of the alignment of the rail route (i.e. the minimum radius of curves, the ruling grade, the minimum of trackwork between grade changes and the crossing loop spacing) is related to the demand of the railway venture. From a cost-effective perspective, the ruling grade and curving of the horizontal alignment impact the creation of earthworks volumes and the cutting configurations.

The quantification of volumes of cuttings versus cutting depths for cutting lengths

The earthworks volumes sub-model quantifies the relationships between the capital cost for specific cutting configurations and the linear track work, allowing the trading off against the train hauling performance and the variable cost of freight haulage. In the case of projects with high demand

Table 1 Systemic operations of the production factors in terms of capex and opex

| Description of production factors	Description of related capacity	The effect of the systemic operations of the production factors in terms of capex and opex
The track length	Selected as the base case (Abril *et al* 2007)	The capex to create the route length
The power of the type of diesel-electric locomotives	Horsepower related to three types of GT-ac locomotives was made relevant (Lozano *et al* 2019)	The capex to deploy the adequate rolling stock on a project
The energy usage capabilities of the haulage power	The fuel usage efficiency of the locomotives related to the gradients of trackwork (Scheffel & Von Gericke 1983)	The opex for the haulage process of freight
The payload of the freight to be carried by train consists	Net tonnes (payload) per train consist (Roney 2015)	The capex to deploy the effective type of rolling stock to haul freight at the required payload
The rolling-stock fleet size	The number of locomotives and wagons required to affect the project's haulage process capacity	The capex to acquire the rolling stock fleet. The opex to maintain the rolling stock fleet
Track super- and sub-structure capacity	Rail type / sleeper type / sleeper spacing / ballast thickness under the sleeper. Layer thicknesses of soil material properties to withstand the axle loads and repetitions during its design life (Roney 2015; Esveld 1989; Lombard 1976)	The capex to construct the super- and sub-structure and the opex for maintenance input
The train crossing capacity per railway route	The number of crossing loops on the mainline, the crossing loop length and the spacing of the loops (Kreuger 1999; Prince 2015)	The capex to construct the train crossing facilities to create train crossing capacity
The maximum number of operative train slots per day	The number of trains in the laden and empty directions to be operated on the mainline daily (Kreuger 1999)	The capex to construct the crossing loops to the required length to accommodate the designed train consist and braking distance
Maintenance depots and facilities	The number of bays in workshops, lengths of loops in staging yards and maintenance equipment	The capex to construct facilities, and the opex to maintain the facilities
Staff	The staff structure	The opex to deploy and remunerate staff
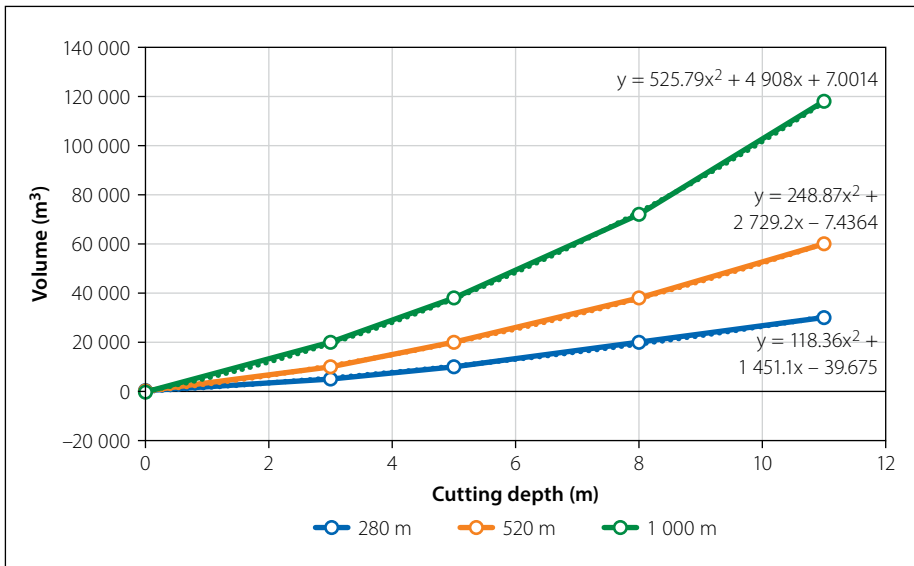
Figure 2 The volume of cuttings versus cutting depths for cutting lengths derived from Simpson's Third Rule (Dhali *et al* 2019)

Graph annotations:
- $y = 525.79x^2 + 4\,908x + 7.0014$
- $y = 248.87x^2 + 2\,729.2x - 7.4364$
- $y = 118.36x^2 + 1\,451.1x - 39.675$

Legend: 280 m, 520 m, 1 000 m

Table 2 Types of track material application for demand and permissible axle load

Description of parameter	Track material configuration in terms of demand (Mtpa) ranges			
	0 – 10	10 – 16	16 – 22	22 +
Permissible axle load* (ton/axle)	18.5	18.5 – 22	22 – 26	26 +
Rail profiles* (kg/m)	48	48	57	60 +
Type of prestressed concrete sleeper*	E3217	E3217	E3217-E3250	E3250
Sleeper spacing* (mm)	700	650	600	600
Ballast thickness under sleeper* (mm)	200	220	250	300
Ballast volume/km** (including 15% compaction)	1 637	1 711	1 967	2 548
Sources: * Lombard (1976), ** Calculation of ballast volumes by authors				

Table 3 Characteristics and parameters for the design of horizontal alignment of trackwork

Design aspect	Track geometric design criteria for horizontal alignment
Horizontal curves for mainline*	Curve radius R = 400 m (min) (preferred radius = 600 m) (Lombard 2017)
Transition curves**	Length of transition curve = 80 m (no transition curves required if the train speed < 15 km/h in yards)
Horizontal curves for crossing loops**	Minimum radii of curves following 1:12 turnouts: R = 300 m
Horizontal curves in yards and sidings**	Minimum radii of curves following 1:9 turnouts: R = 173 m in yards
Sources: * Lombard (2017), ** SAR & H (1968)	

Table 4 Characteristics and parameters for the design of vertical alignment of trackwork

Design aspect	Track geometric design criteria for vertical alignment	
Vertical gradients for mainline*	Loaded train maximum (ruling grade)	Preferred 1 in 66 (1.515%) as a base case
	Empty train maximum (ruling grade)	Preferred 1 in 66 (1.515%)
Vertical curves**	Running lines: 40 mm / 20 m / 20 m (K = 100) Staging lines: 240 mm / 20 m / 20 m (K = 16.67)	
Gradients for crossing loops**	The steepest gradient at which a locomotive can gain traction to depart with a wagon consist is applied. In the case of roller-bearing bogies, the steepest gradient will be 1:800	
Vertical gradients for yards**	Flatter than 1:800	
Minimum length of trackwork between vertical curves**	The train length shall not negotiate more than one vertical curve at any point in time	
Sources: * SAR & H (1968), ** Lombard (2017)		

values, the degree of curvature can be reduced as well as the ruling grade, resulting in deeper cuttings becoming feasible.

The relationship between the depth of a cutting and the unit volume/m is indicated in Equation 1.

$$V = s \,.\, D.^2 \,(b \,.\, D) \qquad (1)$$

Where:
V is the unit volume (m³/m)
s is the side slope of the cutting (ratio)
b is the width of the cutting floor (m)
D is the maximum cutting depth (m).

The spectrum of several formations of cuttings was grouped in classes of dimensions en route sourcing the fill material of the sections of embankments, which was configured in a sub-model (Skempton 1996).

The quantities of cuttings were calculated using Simpson's Third Rule (Dhali *et al* 2019). The volume of cuttings versus the maximum cutting depths for selected cutting lengths is shown in Figure 2.

The cut-to-bank and borrow-to-bank quantities were deduced, including all ancillary costs of related earthworks items, and priced in a Bill of Quantities, which informed the capex in the design model (Duffy 2018; Preston 1992; Dhali *et al* 2019).

PARAMETERS FOR THE DESIGN OF THE TRACKWORK SUPERSTRUCTURE DESIGN

The parameters for the track superstructure design were based on the ramp-up of demand ranges and, consequently, the associated permissible axle loads. The composition of trackwork material in the trackwork sub-model was linked with ranges of axle loads, as shown in Table 2.

Characteristics and parameters for the design of the alignment of trackwork

The characteristics and parameters which were applied in the design of the horizontal alignment of a greenfield section of new trackwork in Southern Africa are set out in Tables 3 and 4.

The characteristics in Table 4, read in conjunction with Table 3, were applied in the design of the vertical alignment of the trackwork.

A summary of the track material and construction items composing the Bill of Quantities is described in Table 5.

The composition of the Bill of Quantities for mainline trackwork, crossing

Table 5 Track material application and construction items in the Bill of Quantities

Track material items in the Bill of Quantities
Track materials
Track route length (m)
Rails (tons)
Rail lengths (for welding purposes)
Sleepers, prestressed concrete type (each)
Sleeper fastenings and pads (each)
Ballast (m³/km)
Turnouts (each)
Rail buffers (each)
Turnout tumblers (each)
Rail lengths (number)
Ballast stone (m³)
Stop blocks (each)
Standard lever box (each)
Level crossing blocks (each)
Perway material totals
Construction items
Miscellaneous:
Survey and set out
Install rail buffers
Provide precast blocks and build level crossings
Manufacture and install kilometre and half-kilometre posts
Provide and install road warning signs at the level crossings
Provide and install track warning signs (whistle boards)
Laying of rails
Offload and stack rails
Distribute rails
Curve rails
Lay rails (including fastening to sleepers)
Destress new track
Distribute sleepers and fastenings
Laying of sleepers
Offload and stack sleepers and fastenings
Distribute sleepers and fastenings
Place sleepers in position
Ballasting and tamping
Transport and stockpile ballast
Load from stockpile, distribute, lift and tamp, box and trim
Turnouts
Offload, stack and distribute turnout components
Build new turnouts in final position – including box, lift and align
Field welding of rail joints:
Flash-butt welding of rail joints in the track
Thermit welding of rail joints in turnouts
Radiographic and ultrasonic testing of welds
Sub-total: Perway material and construction items
Plus: Site establishment
Total construction items in the Bill of Quantities

Table 6 The ratio between earthworks costs and trackwork costs related to gradient and maximum cutting depths for lengths of track route

Ruling gradient	Cutting depth (m) and route length adjustment factor	Number of cuttings	Direct route length (km)	Increased route length (km)	Earthworks cost / trackwork cost
1 in 66	5 (1.025)	250	500	512.50	0.8999
		375	750	768.75	0.8954
		500	1 000	1 025.00	0.8931
		625	1 250	1 281.25	0.8921
1 in 80	8 (1.010)	250	500	505.00	1.2027
		375	750	757.50	1.2023
		500	1 000	1 010.00	1.2011
		625	1 250	1 262.50	1.1827
1 in 132	11 (1.0025)	250	500	501.25	1.5522
		375	750	751.875	1.5559
		500	1 000	1 002.50	1.5562
		625	1 250	1 253.13	1.5577

loops, and yards was developed by obtaining its trackwork quantities as follows:

- The mainline track length, based on the rail route length, was adjusted with a stagger due to the topographic undulation effect (Kweon & Kanade 1994; Riley *et al* 1999).
- The number of turnouts was informed by the number of crossing loops and the number of staging lines in the yards.
- The lengths of the crossing loops and staging lines were deduced from the train length and braking distance of the trains.
- The number of staging lines in yards was related to the demand and the number of train sets.

The trackwork investment estimates informed the cashflow projections in the financial model.

Cost relationship between the macro geometric layout of the linear track structure and earthworks volume

To determine the ratio of cost between the macro geometric layout of the linear track structure and earthworks volumes, a set of parameters was applied in the case of the steepest gradient of a railway line, namely 1 in 66. In this regard, the gradient and maximum cutting depth for lengths of track route and the ratio between earthworks and trackwork costs were determined and are shown in Table 6.

As a form of augmenting the range of parameters, the maximum cutting

depths for rail routes were paired to corresponding ruling gradients, as shown in Table 6. Route lengths were adjusted by adding 2.5% in the case of the 1:66 ruling grade, 1.0% for the 1:80 ruling grade and 0.25% for the 1:132 ruling grade. The ratio of earthworks cost to trackwork cost for the route lengths varying from 500 km to 1 250 km is shown in Table 6 and illustrated in Figure 3.

The ruling grade, as the independent variable, was plotted in Figure 3 on the x-axis, and the ratio of earthworks cost / trackwork cost was plotted as the dependent variable on the y-axis.

- The maximum gradient for trackwork was selected as 1 in 66 (1.51515%) and was paired with 5 m cutting depths.
- The lengths of the cuttings were considered in the cases of the three types of ruling grades with maximum cutting depths of 5 m, 8 m and 11 m, ranging from 280 m to 1 000 m.
- The maximum cutting depth of 13 m was selected. In practice, a railway cutting with a depth of 13 m was assumed to require "benching" by stepping the side slopes at 6 m depth, thereby creating "a cutting within a cutting" (Rauch n.d.).

The equation reflecting the interrelated ratio of earthworks costs / trackwork costs versus ruling gradients for cutting depths up to 13 m was determined by the authors utilising a quadratic fit as shown in Equation 2.
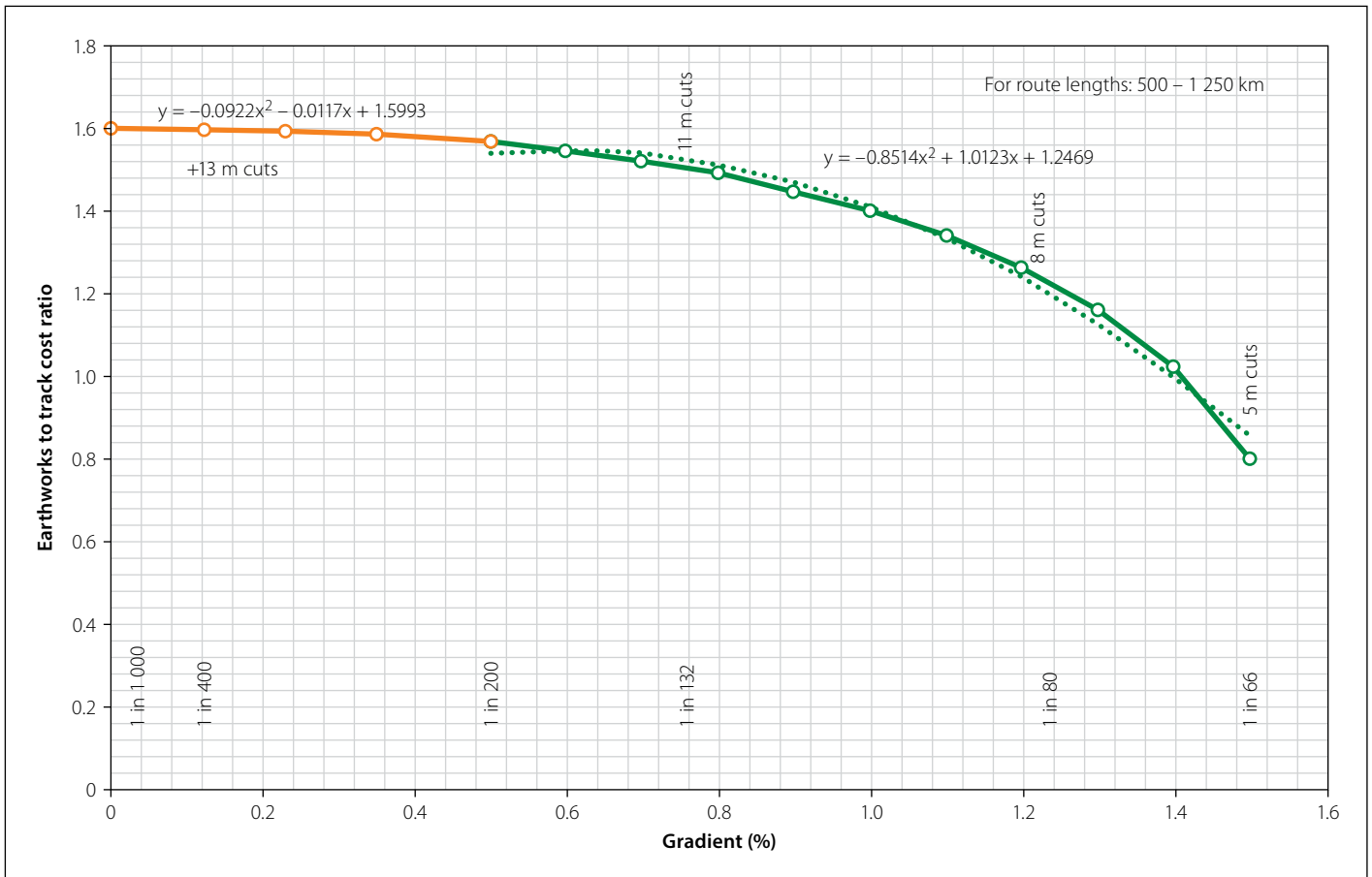
Figure 3 Earthworks costs / track costs ratio versus track gradient

$$y = -0.8514\,x^2 + 1.0123\,x + 1.2469 \qquad (2)$$

Where:
y is the ratio of earthworks cost / trackwork cost
x is the track gradient (%).

The ratio of earthworks cost / track cost versus track gradient in Figure 3 shows that earthworks costs equal the trackwork costs at a gradient of approximately 1 in 72 (1.39%). For grades flatter than 1:200, with cutting depths shown in Figure 3, the earthworks costs exceeded trackwork costs significantly. The ratio of earthworks versus trackwork costs remains constant for gradients flatter than 1 in 200 due to the limitation of 13 m as the maximum cutting depth (Rauch n.d.).

THE HAULAGE PERFORMANCE OF THE ROLLING STOCK

The haulage performance of the train consist was based on the resistive forces acting on the train consist and the train summit speed (Bureika 2008).

The design of the train consist

Davis (1926) formulated the relationship between the rolling resistance exerted on a locomotive during acceleration and attaining line speed. The resistive force (R) that opposes the motion is created by the friction of the axle bearings, the resistance between the wheels and the rail, air resistance, and external forces, as shown in Equation 3 (Mallery 2010). The external forces acting on the train's movement are created by the gradients of the trackwork and its curvature (Coals to New Castle 2017).

$$R = \underbrace{A + B.v + C.v^2}_{\text{Rolling resistance}} + \underbrace{F_C \pm F_G}_{\text{External forces}} \qquad (3)$$

The resistive forces, constants and coefficients are portrayed in Table 7.

Szanto (2016) published test results of the resistive forces on railway vehicles on the Hunter Valley and Pilbara lines in Australia. The values of the constants and coefficients (A, B and C) derived for narrow-gauge rolling stock, are shown in Table 8.

The gross mass (M) for GT38ac, GT42ac and GT46ac type locomotives with axle loads of 18.5 tons, 20 tons and 26 tons gross, respectively, were applied in the hauling sub-model. The train speed (V) of

Table 7 Description of resistive forces, constants and coefficients

Symbol	Description
R	The train resistance comprises the rolling resistance and the resistance imposed by external forces
A	The static and dynamic train resistance component is related to the bogey construction, the axle load, and the inherent mechanical friction of the train set
B	The resistance factor is due to the interaction between the bogeys and the track and is a function of the hunting of the wheelsets
C	The aerodynamic resistance factor generated at the front and rear of the train set and the effect of any additional turbulence
v	The train speed (km/h)
F_C	The curve resistance related to energy dissipation at the wheel-rail interface due to sliding, creep, and friction experienced by rigid bogies
F_G	The resistance instigated by the gradient of the track on the positioning of the train consist

Table 8 Resistive forces on locomotives and railway wagons

Rolling stock type	Rolling resistance force on a locomotive or railway wagon (N/Rolling Stock Vehicle)				Gradient Resistance: (N/loco or per wagon)	Total railway vehicle resistance force: (N/loco) or (N/wagon)
	A (N/loco) or per wagon (N/wagon)	A_0 (N/loco) or per wagon (N/wagon)	B.V. (N/loco) or per wagon (N/wagon)	CV^2 (N/loco) or per wagon (N/wagon)		
Equation constants and variables for locomotives	4.0 (M)	6 (M)	0.046 (V)(M)	0.670 (V^2)	(M)(g) grad%	{(A + A_0 + BV + CV^2) + (M)(g) grad%}
Equation constants and variables for railway wagons	4.0 (M)	4 (M)	0.046 (V)(M)	0.077 (V^2)	(M)(g) grad%	{(A + A_0 + BV + CV^2) + (M)(g) grad%}
Source: Original equation for rolling resistance by Szanto (2016)						

20 km/h at the summit of the line, used by Szanto (2016), was adopted in the design of the train consists. The external force due to the gradient (grad %) and the gravitational acceleration (g) was included in the compilation of the total railway vehicle resistance force.

Resistive forces due to the curvature of trackwork

Scheffel and Von Gericke (1983) designed and developed a self-steering bogie with near-zero curve resistance and virtually no side-wear effect on rails and bogie wheels. In creating a design model, it was assumed that the rolling stock would be fitted with Scheffel-type bogies (Scheffel & Von Gericke 1983; Ball 2016), and consequently the value of the curve resistance force (F_C) was considered negligible (McGonigal 2006).

The design of the train consist

The available drawbar horsepower of a locomotive was determined by solving Equation 4 (Indian Railways Institute n.d.):

available drawbar horsepower =
{((engine to generator hp) × $E_{Transmission}$) −
((total resistance/locomotive) × V)}/270   (4)

Where:
- The power of the GT38ac, GT42ac and GT46ac type locomotives is 2 000, 3 000 and 4 300 hp, respectively
- Transmission efficiency ($E_{Transmission}$) for a GTac type locomotive is 0.94 (Indian Railways Institute n.d.).

The number of laden wagons that a locomotive can haul on a specific gradient with a summit speed (V) of 20 km/h was calculated by dividing the available drawbar force by the resistive force per railway wagon in Equation 5 (Szanto 2016):

number of wagons to be hauled per locomotive = [(available drawbar force) − (total resistance/locomotive)] / (total resistance/wagon)   (5)

The relationships between wagons in the consist versus the gradient for types of locomotives were derived from the equations reflected in Table 8 of which the results are shown in Figure 4.

The haulage design was based on the configuration of train consists and the required number of train trips per year, based on the TAT (turnaround time) and the restriction of the number of train slots per day to convey the required demand.

The design of the rolling stock fleet size

"*The main drivers in determining the rolling stock fleet size of a new railway system for dedicated rail freight (from pit-to-port) are the demand and the TAT*" (Mülke *et al* 2021), as per Equation 6:

the rolling stock fleet size in terms of train consists = {(demand/net mass per train consist)} / ($T_{productive}$ × 24/TAT)   (6)

Where:
- $T_{productive}$ represents the number of productive days of haulage by the railway system during the year
- TAT is the turnaround time (hours).

"*The additional number of wagons and locomotives required at the reduced efficiency levels represented the rolling stock required to operate at the inefficient level of the system to deliver the target demand*" (Mülke *et al* 2021).
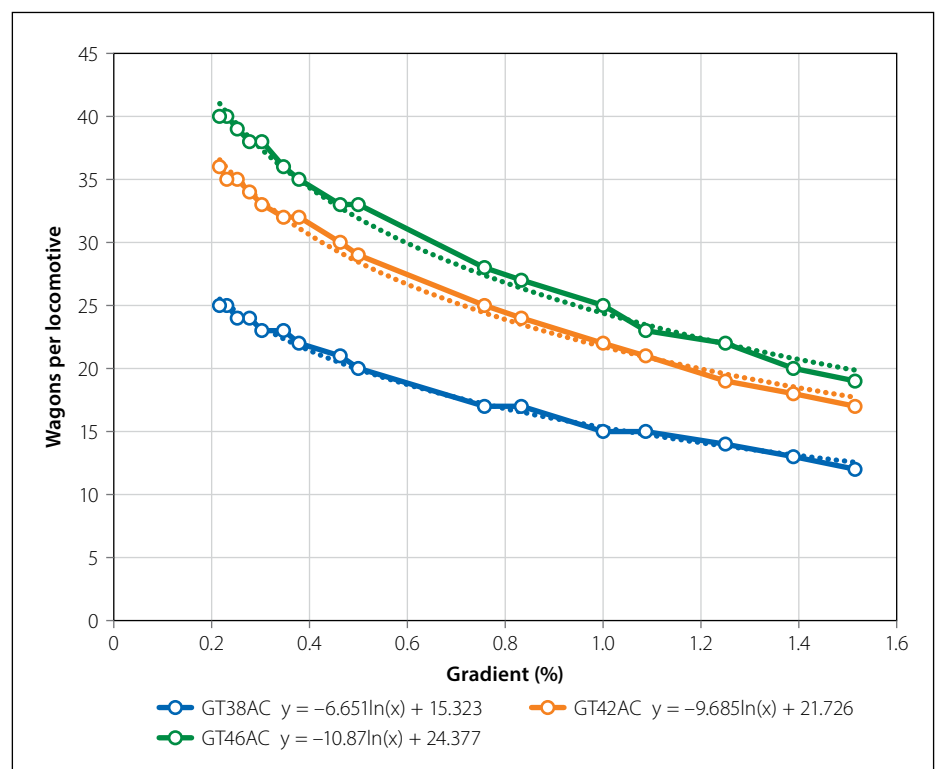

Figure 4 The number of railway wagons per consist versus the track gradient for types of locomotives (Source: Calculated from data provided by Szanto (2016) and equations in Table 8)

Equation (6) was further developed to reflect the rolling stock fleet size concerning the number of locomotives and wagons, which was solved by applying Equation 7:

the locomotive fleet size = (number of locos/consist) * (the rolling stock fleet size in terms of number of train consists)   (7)

The solving of the wagon fleet size can be determined by applying Equation 7 and substituting the number of locomotives/consist with the number of wagons/consist.

The capex of production factors associated with the hauling process was based on the results produced utilising the dashboard process depicted hereunder.

EFFECT OF SYSTEMIC OPERATING EFFICIENCY ON THE CAPACITY OF THE PRODUCTION FACTORS

Systemic operating efficiency (E_{TotEff}), as it relates to the railway environment, refers to the lack of waste (Carr 2016; Prince 2015). The inefficiency of a railway operating system stems from wasted time and, specifically, the resulting increase in the turnaround time (TAT) to affect an increase in production factors (Abril *et al* 2007; Aikaterini 2010; Grosskopf 1993; Jondrow 1982).

The TAT encapsulates all the time-related processes to load a train, operate it through the network, stage and offload the train, stage the empty train, and return it to its origin (Dutton & Mülke 2017). The systemic operating efficiency can be determined by Equation 8:

systemic operating efficiency:

$$E_{TotEff} = \left(1 - \frac{\Delta TAT}{TAT_1}\right) 100\%$$ (8)

Where:
$\Delta TAT = TAT_2 - TAT_1$
E_{TotEff} is the systemic operating efficiency expressed as a percentage $\leq 100\%$
TAT_2 is the TAT at the inefficient performance level
TAT_1 is the TAT at the efficient or design performance level or the efficient reference base case.

The systemic operating efficiency was determined by simulating scenarios for variations in average train speed versus a range of delayed-release times of trains from the inland departure point. The
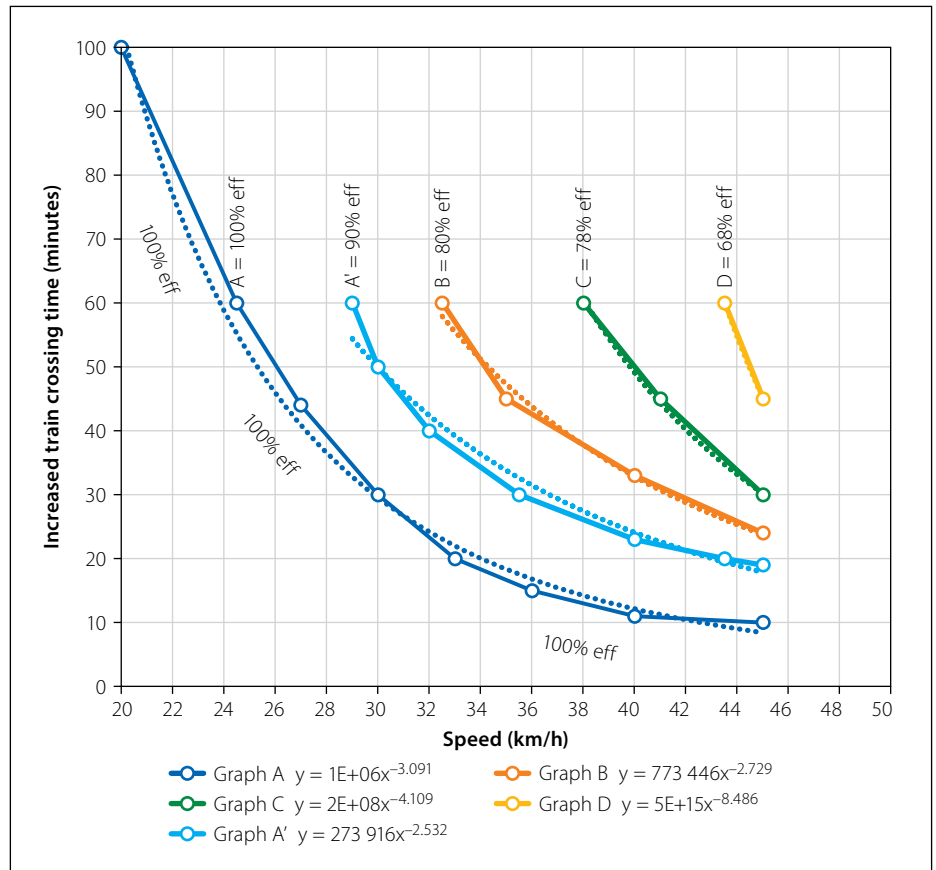

Figure 5 Increased train-crossing time versus average speed for systemic operating efficiency (Source: Mülke *et al* 2021)

constraining factors included the late release of laden and empty trains into the mainline.

The results of the delayed train crossing time versus the average train speed for levels of systemic operating efficiency are plotted in Figure 5. Notably, the E_{TotEff} ranged between 68% and 100%.

The late departure of trains had a diminished effect on the systemic operating efficiency of the system. It had a more significant impact on the system's performance in the case of fast-moving trains and short

dwell times in the endpoint, resulting in the densification of train slots and an increase in the randomness of train movements. A delay buffer time of 25 minutes was conceded in the scheduling of trains and correlated with the Kuys *et al* report (2017).

The efficiency of the application of the fleet size to haul the annual demand compared with the systemic operating efficiency is shown in Table 9.

Comparing the wagon fleet sizes in the case of the systemic operating efficiency decreasing from 1.00 to 0.68, the wagon

Table 9 Effect of systemic operating efficiency on wagon fleet size and internal rate of return (IRR) of a new railway project

Systemic operating efficiency (factor)	Wagon fleet size required (number of wagons)	Increase in wagon fleet size (%)	IRR (%)	Systemic operating efficiency factor of the application of the wagon fleet	The efficiency of application of wagon fleet / systemic operating efficiency level (factor)
Base case: 1.00	1 034	–	18.0	1.000	1.000
0.90	1 154	+ 11.6	17.5	0.884	0.982
0.80	1 268	+ 22.6	17.1	0.774	0.968
0.77	1 309	+ 26.6	16.9	0.744	0.966
0.68	1 425	+ 37.8	16.5	0.622	0.915
Source: Mülke *et al* (2021)					

Table 10 Determinants of the design of railway projects

Determinants	Description
Demand	The primary driver of the design of capacities of the production factors.
Permissible axle load	The axle load is the first determinant derived from the demand and was applied to the design of the rolling stock, the track material, and the earthworks layered system. The permissible axle load is a determinant of the type of track material. The number of axle load repetitions was applied in the calculation of the properties of the earthwork's layered system and the economic life span of the earthworks. The earthworks layered systems and the bridges and culverts are often designed to allow for anticipated increases in axle loads as it could be problematic to strengthen such during the later running of train services.
Ranges of railway operations	The application of the design model covered the range of demand, from low volumes of dedicated freight up to the level of heavy haul. The design model allowed for the capacities of the production factors to be increased as the demand increased. In this regard, sub-models were developed that produced the increase in the cost of the production factors, e.g. the track material and the rolling stock fleet related to increases in demand.
The relationship between linearity and volumetric traits of a new railway network	The capital investment for the earthworks for specific geometric factors and linear-based production factor configurations was compared with the linear trackwork capex to illustrate the relationship between volumetric-linear type production.
The gradient of the rail route	The ruling grade of the rail route was selected in accordance with the demand, the undulating composition of the terrain, the provisional selection of the cutting depths and the resultant train consist. The train consist was derived from the ruling grade of the track design and informed the compilation of the rolling stock fleet size.
The average train speed	The average train speed is a function of the curving of the trackwork and the gradient. The average train speed dictated the turnaround time (TAT) applied in quantifying the rolling stock fleet size.
The route length	The route length is a primary determinant in quantifying the TAT of a train consist and the calculation of the number of train sets required to deliver the freight at a destined port.
Project development life cycle costing	The primary production factors are the rolling stock, track superstructure, and sub-structure. The project development life cycle costing of the production factors was estimated for the construction phase, the ramp-up phase, and the operational steady state of the railway project. The design model allowed for the inclusion of the cost of sustaining capacity requirements using preventative and recovery maintenance interventions and their effect on the useful life of the production factors. The cash flow projections accounted for these intervention costs for calculating the IRR and rail tariff rate.

Table 11 The capex items

Capex
Ancillary civil works and trackwork
Land
Fencing
Earthworks and drainage
Bridges and culverts
Sub-total: Civil and trackwork
Signalling and telecommunications
Signalling mainline
Signalling in yards
Signalling onboard
Telecommunication on the mainline
Telecommunications yards
Sub-total: Signalling and telecommunications
Workshops, buildings, services and facilities
Workshops, buildings and services
Yards and depots: roadways and paving
Mechanical workshops
Wagon repair workshop
Main services in yards
Depot facilities – mechanical
Depot facilities – operating
Depot facilities – infrastructure
Fuel stations
Sub-total: Workshops, buildings, services and facilities
Rolling stock – locomotives
Construction
Shunters
Mainline locomotives
Rolling stock – wagons
Construction wagons
General freight wagons
Container flatbed wagons
Tankers
Specialised mining product wagons
Sub-total: Rolling stock
Equipment
Train gear equipment
Wayside equipment
Infrastructure warning devices
Rolling stock condition monitoring
Mechanical workshops
Permanent way maintenance
Railway recovery cranes
Sub-total: Equipment
Engineering, construction supervision
Engineering consulting and construction supervision
Start-up team
Sub-total: Engineering, construction supervision
Total: Capex

fleet size increased by 37.8%, and the IRR reduced correspondingly from 18.0% to 16.5%.

Applying the systemic operating efficiency factor in the design of train-crossing capacity

The longest section between crossing loops determines the capacity of a single railway line. The train-crossing capacity of a single line (C) is shown in Equation 9 and is a function of the systemic operating efficiency, E_{TotEff}:

$$C = E_{TotEff} \times 1440/\{2((L/V \times 60) + S_t)\} \qquad (9)$$

Where:

C is the train-crossing capacity expressed in the number of laden train slots per 24 hours

V is the average speed of the trains operated between the crossing loops (km/h)

L is the spacing extent between the crossing loops (km)

S_t is the train-crossing time (minutes) in the crossing loop, based on the dwell time of the empty train to allow the laden train to pass and clear the loop

E_{TotEff} is the total systemic operating efficiency of the loading, unloading, crossing and running of trains.

The spacing between the crossing loops (L) for variations in average train speeds and the systemic operating efficiency was solved using Equation 9. The calculation results of the number and length of crossing loops as a function of the train length, the braking distance and train speed were incorporated in the haulage sub-models as a sub-process of the design model and informed the capex (Zuan 2007; The Mathematical Association (UK) 2004).
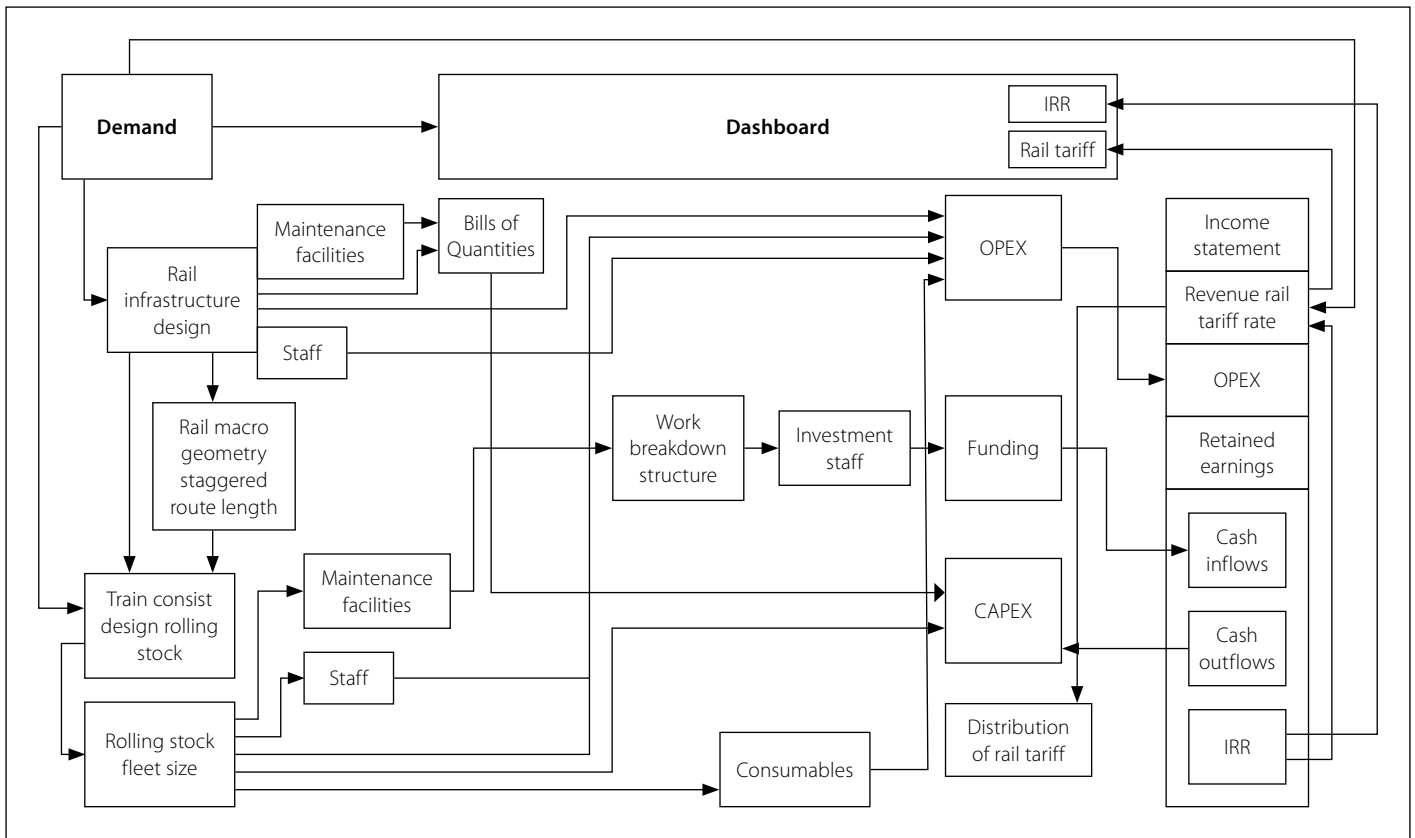
Figure 6 Flow diagram depicting the inter-relatedness between sub-processes, integrated into the dashboard

THE DESIGN MODEL

The design model embodies the demand as the determinant for railway services in design processes to ascertain the capacities of the production factors.

The demand-driven systemic design

The demand can vary in ramp-up rate, the level of steady-state and prospects of increasing the project life at a later stage of the project life cycle.

The determinants of the design of the capacities of the railway project were considered paramount in compiling the interactive sub-systems of the design model and are summarised in Table 10.

The design model as an algorithm

Cormen *et al* (1990) described an algorithm as a *"sequence of computational steps that takes input values and transforms them into output values"*.

The objective of the compilation of an algorithm, holistically referred to as the design model, was to construct the interlinkage between sub-processes in sub-models. The dashboard enabled the selection of input capacities, which then produced the capex and opex of the following main processes:

- The rail infrastructure
- The train hauling process
- The train operations
- The financial modelling.

The input to the sub-models and the design assumptions formed steps in the algorithm to compute the two ultimate output parameters, namely the rail tariff rate (US dollar / net tonne-km) for a given IRR.

The methodology of using the dashboard entailed the following process:
- Determine the demand.
- Determine the input to the rail infrastructure sub-model in terms of the topographical layout of the terrain en route:
  - the staggered length of the line
  - the ruling grade
  - the depth of the cuttings associated with the selected gradient
  - the number of cuttings on the line.

The resultant output of the rail infrastructure sub-model comprised the volumes of earthworks creating the input to the Bill of Quantities and developing the capex value of the earthworks.

The route length and demand produced the input to the trackwork Bill of Quantities informing the compilation of the capex of the rail infrastructure.

Subsequently, the following train performance requirements were selected:
- The appropriate locomotive type for the demand range in which the operations were conducted
- The number of trains per day to be compared with the system's restriction of the number of train slots or trains per day.

As output, the rolling stock fleet size was derived from the configured algorithm using the dashboard. The rail tariff rate was ascertained by realising the required IRR of 20% (Luiu *et al* 2018).

The logic of integrating the input of various sub-processes in the dashboard is illustrated in the flow diagram Figure 6.

In addition to the requirements to assure the performance of the rolling stock fleet size, the demand determined the capacities, and consequently the capex of the production factors as set out in Table 11 (Ghoreishni 2019).

Opex estimate for the project

The typical opex items of a dedicated rail freight project are listed in Table 12.

The construct of the dashboard reflecting the integrated process for determining the rolling stock fleet size and the rail tariff rate for a set IRR is shown as an example in Table 13.

Finally, the cost of creating capacities of the locomotive and wagon fleets was computed as variable capex, varying with the demand, and adjusted following the effect of the level of systemic operating efficiency. An example of the results of a specific scenario of input values that rendered output results is shown in Table 14.

Mülke *et al* (2021) stated: *"A cost structure analysis indicated that the investment cost*

Table 12 The opex items

Opex
Fixed overhead costs
Train operations in headquarters (HQ)
Mechanical maintenance HQ and depots
Infrastructure maintenance
Telecommunications and signalling
Logistical management support
Rental of vehicles
General management and support services ■ Humann resources ■ Financial services ■ Marketing
Other overheads
Fixed concession fees
Sub-total: Fixed overhead costs
Direct fixed costs
Insurance and security
Maintenance: bridges and culverts
Small plant: trackwork and bridges
Maintenance of trackwork
Provisions for contingency
Sub-total: Direct fixed costs
Direct variable costs
Salaries of train crews
Expenditure on fuels
Expenditure on lubricants
Locomotive maintenance material
Wagon maintenance material
Insurance on locomotives and wagons
Concession fees (variable)
Staff salaries
Ex-pat salaries
Sub-total: Direct variable costs
Total: Opex

of rail infrastructure can comprise 20.2% of the rail tariff and that the rolling stock and haulage costs can comprise the remaining 79.8%. The haulage costs mainly consist of variable capex and opex over the short and long term (Parajuli 2005). In contrast, the rail infrastructure costs consist of investment in the track length, the number and lengths of crossing loops and the ancillary civil works."

RESULTS

The rail tariff distribution of train consist hauled by types of locomotives

The rail tariff of the haulage process for the deploying of the types of locomotives GT38ac, GT42ac and GT46ac, was derived from the application of the algorithm expressed in selecting the variables in the dashboard.

Table 13 Steps to be followed on the dashboard for determining the rolling stock fleet size and the rail tariff rate

Dashboard		
Inputs	**Quantity**	**Description**
Demand: Mega tonnes per annum (Mtpa)	8.0	The demand is the primary driver of the systemic design and serves as the final correlation of the performance of the production factors operating in concert.
Mechanical efficiency (loco)	0.94	Select the locomotive mechanical efficiency ranging from 0.85 – 0.94 for types of locomotives.
Loco availability	95%	Select the locomotive availability based on the age and condition of the locomotives.
Wagon availability	93%	Select the wagon availability based on the age and condition of the wagons.
Gradient – 1 in …	66	Select the ruling grade based on the demand.
Average speed (km/h)	33	Determine the train's average speed considering the track's vertical and horizontal alignment and the momentum swing in dynamic train control.
Buffer time (min)	25	Select the buffer time not exceeding 25 minutes.
Systemic efficiency (factor)	0.80	Select the systemic operating efficiency factor.
Design train slots/day	8	Determine the maximum number of train slots/day based on the dwell times of the trains in the loading and off-loading endpoints.
Crossing time duration loaded (min)	8	Select the crossing time of loaded trains depending on the speed in the crossing loop and the length of the train.
Crossing time duration empty (min)	10	Select the crossing time of empty trains depending on the reduction of speed in the crossing loop, the braking time and the stopping distance based on the length of the train.
Locomotive type	GT38ac	Select the type of locomotive based on the demand and the appropriate locomotive's power.
Number of locomotives in consist	5	Compare the output of trains per day with the set maximum number of slots. If the design number of slots exceeds the maximum number of slots as a restriction, then increase the number of locomotives, and thereby the train consist of utilising fewer train slots.
Wagon axle load (tons/axle)	18.5	Select the permissible axle load of the line and, resultantly, the axle load and net payload of the wagons.
Train crew changes per trip	4	Calculate the crew changes considering the maximum shift time specified in the specific country.
Availability of train crews (%)	80%	Allow for redundancy in train crews.
Output results (calculations)	**Quantity**	**Description**
Locomotive axle load (tons/axle)	18.5	Derived from the type of locomotive deployed.
Wagons/locomotive	12	Output results derived from the formulae based on the power of the locomotive, the train resistance on the designed gradient and the balancing speed at the summit of the vertical curve.
The number of wagons in the consist	60	Output result based on the required capacity of the train consists of hauling the required demand and operating within the restriction of the designed number of slots per day.
Load/wagon (payload: tonnes)	53.15	Derived from the permissible axle load.
Nett. tonnes/consist	3 189	Derived from the gross load/wagon multiplied by the number of wagons in the train consist.
The total number of trainsets required	16.77	Based on the demand and capacity of payload per trainset, it is based on the TAT.
Trains per day calculated	7.2	The required number of train slots per day considering the design restriction of slots/day and the required train consist of hauling the demand.
TAT (hrs)	56.15	The TAT (or cycle time) is calculated considering the transit times of the laden and empty trains, the dwell times at the loading and off-loading endpoints, the buffer times, and the systemic operating efficiency factor.
Train trips per annum	2.509	Output result
Number of crossing loops required	15	Output result
The total length of crossing loops (km)	23.910	Output result
Number of locomotives required	89	Output result
Number of wagons required	1 082	Output result
Rail tariff rate (USD per net tonne-km)	0.050	The result of the financial analysis determined the rail tariff rate with an iterative method in conjunction with the pre-determined IRR.

Table 14 Total tariff for rail infrastructure work and haulage operations

Description	Capex tariff component (USD/ton) (1)	Total opex tariff component (USD/ton) (2)	Capex + total opex tariff components (USD/ton) (3) = (1) + (2)	IRR markup distributed as a tariff component (USD/ton) (4)	Total tariff per asset group, including distributed IRR markup (USD/ton) (5) = (3) + (4)	Percentage of the total tariff (%)
Trackwork and civil work	1.665	1.740	3.405	2.343	5.748	20.20
Rolling stock:						
- Locomotives	0.885	11.756	12.641	8.700	21.341	74.98
- Railway wagons	0.450	0.363	0.813	0.559	1.372	4.82
Total hauling tariff	1.335	12.119	13.454	9.259	22.713	79.80
Total tariff of capex and rail infrastructure opex and haulage costs components (USD/ton)	3.000	13.859	16.859	11.602	28.461	100.00
Source: Mülke *et al* (2021)						

The capacities of the production factors were determined for the various demand levels and informed the investment schedule and the cash flow statement. Finally, the capacities of the locomotive and wagon fleet sizes were computed as variable capex, varying with the demand, and adjusted by the level of systemic operating efficiency.

In Figure 7, the tariff rate versus demand for types of locomotive traction was plotted for a systemic operating efficiency factor of 0.90 and variation in route lengths.

The rail tariff rate decreased with the increase in route length and was attributable to the effect of earthworks costs incurred at the two endpoints. The product of the route length and the rail tariff rate rendered the tariff expressed in USD/tonne, which increased with the increase in route length.

The long-term and short-term average cost curves

The concept of economies-of-scale refers to the potential of using the unused capacity of a railway system at marginal increases in input cost. The use of track-carrying capacity (train slots/day) that is available for the increased haulage of additional volumes is an example of the use of "economies of scale" (Samuelson 1970). The effect of economies of scale and dis-economies of scale is calculated during the quantification of the long-run average cost curve (LAC) (Pettinger 2019; BCampus Open Publishing 2019; Chen 2007). This aspect was contained in a cash flow projection, which formed the basis of the design model for determining the rail tariff rate and the IRR (Luiu *et al* 2018).

As an increasing number of trains absorb the capacity of the fixed assets, the lowest average haulage cost at that point of haulage activity is reached, after which it will increase when additional capacity is required. The new level of capacity creation can be in the form of longer trains with additional locomotive power, which would entail additional capital investment. The next stage of capacity increase would involve increasing the axle loads of the rolling stock. In such a case, further capital investment would be required in the track superstructure and the carrying capacity of the rolling stock, e.g. heavy-haul vehicles (Denley 2018; Tourney & Fröhling 2015).

The cost productive indicator net tonne (CPINT)

A cost-productive indicator net tonne (CPINT) was compiled based on the variables in Equation 10, namely:

$$CPINT = (C \times E_{TotEff})D/NT \qquad (10)$$

Where:
CPINT is the cost productive indicator of net tonne hauled
   C is the total average cost (USD/tonne)
   D is the demand (Mtpa)
E_{TotEff} is the systemic operator efficiency factor
  NT is the production activity indicator represented by the payload of the wagon consist (net tonne).

The payload of the wagon consist is an indicator of the train unit's conveying capacity based on the axle load as specified and hauled by one of the GT38ac, GT42ac or GT46ac type locomotives.

The demand/net tonne of wagon consist is representative of the number of train trips per year and is indicative of the activity effort of the haulage process. The CPINT was devised as an indicator based on the format of (haulage cost) × (annual hauled quantity) / (production activity indicator).

The production activity indicator was selected as the wagon consist payload (train payload), which was designed considering the ruling gradient and the permissible axle load. In the case of demand being low, the NT will be low due to steep gradients, and the result is a high CPINT value of which a plot replicates the typical parabolic shape of short-term average costs (SAC) curves.

Similarly, if the demand is high and the production activity indicator is high due to flat gradients, the CPINT calculation renders low values as is the case with heavy-haul train operational results.

Individual curves were plotted from CPINT values versus demand for haulage by locomotive types GT38ac, GT42ac and GT46ac on a gradient of 1 in 66, as shown in Figure 8.

The following observations concerning the graphic plot of CPINT results were made:
- The results formed a series of "strings" of parabolic shape, of which the lowest value represented the "vertex" of the envelope curve. Each "string", or parabolic curve, represented the application of a locomotive and a wagon consist configuration and the hauling capacity expressed in terms of the payload of the conveying unit.
- On the range of the **downward slope** (O–A, C–D and F–G) of the CPINT curve the volumes were increased due to the increase in conveyance effort created by the increased number of trains
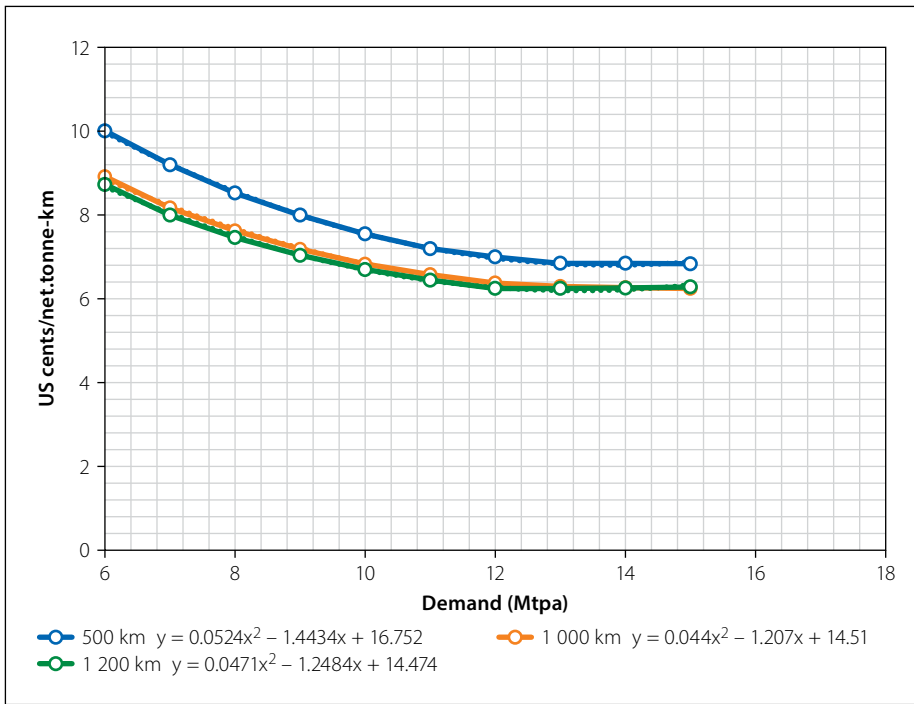
Figure 7 The tariff rate versus demand for variations in route length
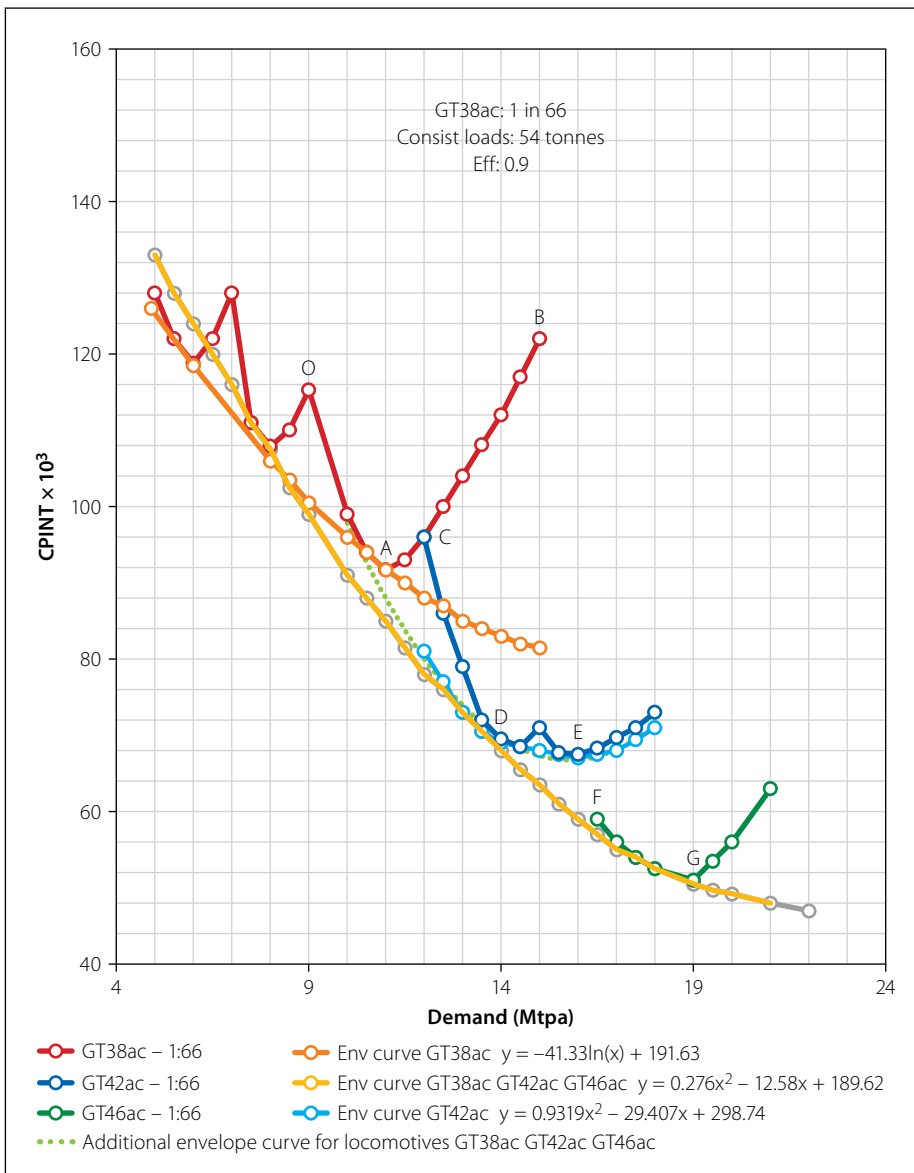

Figure 8 CPINT values versus demand for locomotive types GT38ac, GT42ac and GT46ac haulage for track gradient: 1 in 66

(Prince 2015). The maximum efficient operating capacity was represented by the ordinates of the vertex of the curves (A, D, E and G).

- On the range of the **upward slope** of a curve (A–B), dis-economies of scale were experienced due to increasing train speeds, the resultant variability and randomness occurring in train operations, and the exceedance of the in-built buffer transit times.
- **At the vertex points** (A, D, E and G), the axle load could either be increased, or the train consist be supplemented to create additional haulage capacity. The shape of the envelope curve resembled the Harris curve for railway costs versus track density (Harris 1977; De Bod & Havenga 2010).

The CPINT values decreased from a demand of 5 Mtpa to 13 Mtpa for a maximum train consist of 7 locomotives and 84 wagons. This was due to the diluting of fixed costs and capacity utilisation on the mainline, exhausting the "economy of scale".

The train operations capacity was restricted to 8 trains per day in the utilisation of train crossing capacity. If the consist capacity of 7 locomotives and 120 wagons was reached (at C), the traction power was increased by deploying a more powerful type of locomotive to operate within the train crossing restrictive capacity. Consequently, the wagon consists were extended, and the axle loads increased (at C) instead of running additional light axle-loaded trains to meet the demand (Boysen 2012b).

The result was that the CPINT ordinates for the GT38ac, GT42ac and GT46ac traction scenarios reduced versus increases in demand due to the deployment of additional capacity in terms of haulage power (red, blue and green curves), train consist and train-crossing capacity in terms of crossing-loop configuration.

CONCLUSIONS

The main objective was attained by compiling a design model that integrated the design processes of capacity creation of production factors influenced by systemic operating efficiency. The sub-objectives in this research study were also achieved, namely:

- Sub-objective 1 was met by establishing a sub-model to determine the interrelationship between the macro geometric layout of the linear track structure and earthworks volumes.

- Regarding the attainment of sub-objective 2, the correlation of the haul-age performance of the rolling stock related to the macro geometric track alignment and the demand, was met. In this regard, a sub-model was compiled that relates the track gradients to the performance of train consists.

- In pursuing sub-objective 3, the effect of total systemic efficiency levels on the rolling stock's capacity was deter-mined. Simulation results informed the definition of parameters applied in the haulage sub-model. The systemic operating efficiency was deduced from scenarios of inefficient performance of train operations and the impact thereof on capacity creation and interrelated internal rate of return (IRR) quantified.

- Sub-objective 4 was met in terms of structuring a design model that inte-grated the capacities and processes of a railway system. The impact of levels of inefficient operating on the IRR was derived from the financial results of the design model. The design model was developed to integrate and optimise the production factors and to determine the financial viability of a dedicated rail freight project.

The conclusion is drawn that a reduction in total systemic efficiency results in the increase of the capacity of production factors, i.e. rolling stock fleet size and, consequently, the capex and opex, which results in the escalation of the tariff rate or reduction of the IRR of a railway venture.

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