A Decision Support Method for Designing Vegetation Layers with minimised Irrigation Need

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Abstract

Selecting a vegetation layer design goes along with determining its future irrigation need. Therefore, it is essential to take a design decision that is minimising the cumulated construction and irrigation costs in a given depreciation period. This contribution showcases a decision support approach using long term weathering time series and soil water balances with example data for turf soccer fields in six German regions. The approach relies on minimising both material and irrigation costs by modifying soil layer design parameters; here the layer thickness and therefore its water retention capacity. E.g. suggested layer thicknesses between 200 and 250 mm for Stuttgart lead over 10 to 40 year depreciation periods to estimated substrate and water cost savings between 90 and 194 % in comparison to a standard substrate layer thickness of 80 mm. For practical applications, the presented theoretical approach needs to be adapted with the usable soil water storage capacity and relationships describing evapotranspiration for given substrate-turfgrass combinations.

1 Introduction

1.1 Presentation of the Problem

The consortium of the German research and development project RasenTex [1] develops a novel modular design model for vegetation layers for turfgrass like on soccer fields or e.g. in parks with enhanced water permeability and storage capacity. The motivation is a market gap for economical vegetation layers with both minimised irrigation need and excellent percolation. The design model relies on regionally available substrate components and specially designed textile structures with optimised capillary properties[1]. Besides increasing the annual soccer field usage time, one major objective is to reduce irrigation need [2] and therefore maintenance costs.

For vegetation layers, there are usually different technical design models available. Evapotranspiration of the vegetation layer and local weather conditions should be considered as well for designing the vegetation layer's water storage capacity. An interesting – up to now intensely discussed, but not commercially addressed – recurring cost block forms the influence of local weathering on maintenance costs.

[1] Textile structures do feature capillary properties that may complement those of vegetation layers: e.g. adsorption volumina of 100...1,000 mass-% or capillary rise levels up to 50 cm and more with comparatively high hydraulic conductivity values are common material properties for nonwovens designed as fluid absorbers [3]. Hence, these materials do form interesting aggregates for soil substrates, as their hydraulic conductivity is much higher than in soil substrates [1].

Vegetation layer planning and construction companies do choose technical design models for projects in function of compliance to the required qualitative features and costs. Besides choosing the most cost effective vegetation layer design model, they configure it in such manner that both its construction and recurring (here irrigation) costs are minimised while preserving the design model's qualitative features. Unfortunately, there is no method available for adapting vegetation model design parameters in function of construction and recurring costs like irrigation, so far.

1.2 Objectives

Companies designing and planning gardens, landscapes like parks as well as sport grounds need to be able to discuss, offer and select the best layer structure and to find optimal layer thicknesses with minimised substrate and irrigation costs in terms of local long-term weathering conditions.

This contribution showcases a metaheuristic optimisation approach for parameters in given vegetation layer design models in terms of long-term weathering, construction and irrigation costs by the example of small to medium sized soccer club fields in different moist and drier regions of Germany.

1.3 Overview

This work is structured as follows. The presentation of the foundations in section 2 starts an overview of commonly used design models for soccer fields in Germany. Then, a suitable evapotranspiration model and time series are chosen. Following, the soil water balance, economical assessment criteria as well as the optimisation approach are described. Section 3 describes the chosen approach. After some general specifications, a stock-flow model for the water balance in vegetation layer substrates is presented. Then, the cost assessment model for a simulation run is presented, followed by the optimisation approach and the presentation of exemplary results. The concluding discussion of the results in section 4 shows points of improvement for the modelling approach and features potentially interesting aspects for key stakeholder groups. Section 5 summarises the conclusions.

2 Foundations

2.1 Technical Design models for Soccer Fields in Germany

The following standardised technical design models are available [4][2]:

- DIN 18035-4 Sports Ground - Part 4: Sports turf areas [5].
- RAL GZ 515/2 Factory-produced turf soils […] for sports grounds [6].

The USGA recommendations for golf courses [7] are occasionally in use as design model, as well.

The German Football Association (Deutscher Fußballbund, DFB) [5] recommends a substrate layer thickness of 80 mm without, and 120-150 mm with a drainage layer, below. [6] relies on a substrate layer thickness of 120 mm with a drainage layer, below. Both standards rely on special grading curves to assure a sufficient water permeability as well as adequate capillary moisture storage. As both approaches are rather costly for small soccer clubs, sports field constructors do offer these clubs individualised solutions, using e.g. quartz sand and local topsoil, adapting sometimes the design guidelines for golf courses (e.g. [7] refers to the standard [8]; the German standard is [9]) with 300 mm substrate layer thickness.

The vegetation layer design models in RasenTex [1] follow the recommendations in [5], but do explicitly use locally available soil components and a layer system that is adapted to local weathering. This may result in substantial economical savings by designing e.g. the layer thickness just as high as necessary or by mixing the substrate components on site using locally available materials.

Soil water storage capacity in sports grounds substrate layers is in general bigger than in the locally available soil, as components with medium coarse, voluminous pores between the grains (e.g. sands) and pores inside the material (e.g. some lava types, expanded clay) are being used. Typical values for soil water storage capacity for turfgrass substrate layers are between 10..20 % water mass per substrate mass; USGA recommends substrates[3] with water storage capacities between 15..25 %.

[2] [4] pp92 gives further specific construction and irrigation recommendations.
[3] For optimal substrate mixtures, see e.g. [10].

In general, available soil water is estimated as the difference between field capacity[4] as an upper limit for water available for plants and remaining soil water at the permanent wilting point. However, irrigation recommendations for turfgrass sports fields DFB [4] state to irrigate when wilting starts, thus e.g. reducing susceptibility to infections. Therefore, slightly reduced values for the relative soil water storage capacity will be used, here. These will be called “*usable* soil water storage capacity”.

In order to ensure playability on the sports ground after heavy rainfall, the soil under the vegetation layer should have better drainage capabilities than the vegetation layer. If necessary, a dedicated drainage layer is placed under the vegetation layer. This implies that there is a capillary break below the vegetation layer.

2.2 Modelling Evapotranspiration

Evapotranspiration describes “*the loss of water from the Earth's surface to the atmosphere by the combined processes of evaporation from the open water bodies, bare soil and plant surfaces, etc. and transpiration from vegetation or any other moisture-containing living surface.*” [13]. [14] provides a review on the subject. The evaporation models being most popular in Germany form the Penman-Monteith model [15], [16], [17] and the Haude model [18]. However, the German standard for irrigating sportsgrounds [19] relies on a simple approach by calculating daily evapotranspiration in function of the day’s highest temperature value. As this approach is inferior to the Haude model, it is discarded, here. The Haude model covers potential evapotranspiration, only, whereas the approach of Penman-Monteith can be adapted to cover real evapotranspiration, as well, by taking available soil water into account. The Penman-Monteith model is the most recommended one, but needs more input data and calculation effort.

The Climate Data Center (CDC) of Deutscher Wetterdienst provides for many localities in Germany weathering time series with daily resolution [20][5]. For selected weather stations[6], Deutscher Wetterdienst provides calculated daily values of the real and potential evapotranspiration over grass and sandy loam [22] using the AMBAV [23] model[7] and the potential evapotranspiration following the Haude model.

The following requirements do apply when selecting an evapotranspiration model for turfgrass on soccer playgrounds:

(a) Soccer playgrounds are irrigated and fertilised for providing optimal playing conditions.
(b) The usable water storage capacity by the local turfgrass on the substrate layer is not known.
(c) There is often a drainage layer under the substrate layer.

Constraint (a) implies that an evapotranspiration model with potential evapotranspiration should be chosen, as there is always sufficient water available. (b) could be overcome by capturing evapotranspiration lysimeter and local weathering time series of the artificial vegetation layer and estimating the usable water storage capacity. This permits as well building a regression model for evapotranspiration. Restriction (c) is limiting the substrate layer’s capillary water storage capacity by introducing a capillary break towards the foundation soil. If no real overgrown substrate layer-specific evapotranspiration time series are available, it is suitable to choose an evapotranspiration time series representing potential evapotranspiration.

Figure 1 shows an exemplary plot of two estimated potential evapotranspiration time series over the estimated real evapotranspiration [27][8]. It can be seen that the estimated time series for potential evapotranspiration over grass and sandy loam (AMBAV) VGSL does always scatter above the corresponding real evapotranspiration value, as it does not take stored water in the ground into account. The estimated time series for potential evapotranspiration over Grass (Haude) CPGH is sometimes underestimating real and potential evapotranspiration.

[4] See e.g. [11], [12].
[5] [24] provides a zoomable map of all currently functional weather stations in Germany, using data from [21]. [25] gives a data set description.
[6] [24] links to a zoomable map with weather stations with evapotranspiration time series, using data from [26]. For the dataset description, see [20].
[7] An adapted version of the Penman Monteith model.
[8] The time series is for Merseburg/ Saale, station index 445, 84 m above mean sea level, latitude 51.82°, longtitude 11.71° in Saxony-Anhalt, from 31/03/2017 to 30/09/2017.

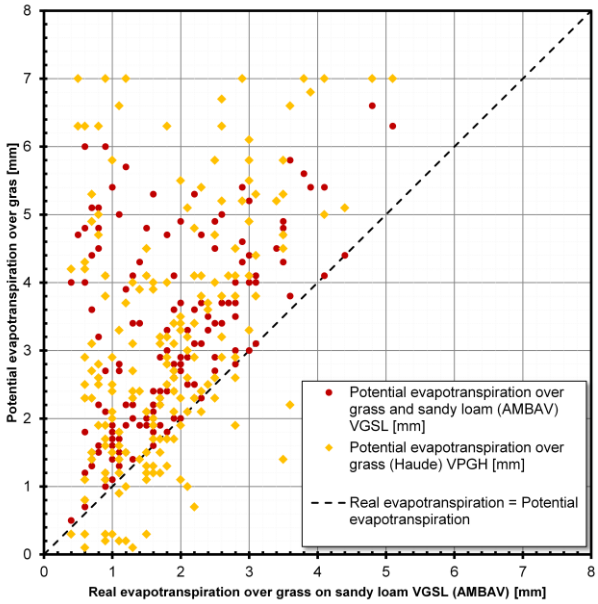

Figure 1: Estimated potential over real evapotranspiration plot, basing on [27]

For the purpose in this work, the estimated time series for potential evapotranspiration over grass and sandy loam (AMBAV) VGSL [27] are chosen, as their values can be seen as upper borders for real evapotranspiration on irrigated and fertilised soccer playgrounds. Hence, vegetation layer design optimisation will be carried out implying inferior conditions as in real world. This will lead to slightly more conservative design parameters “on the safe side” than actually necessary.

2.3 Soil Water Balance

Soil water balances are well-described and easy to integrate in simulation models [17], [28]. Typical modelling components form:

(a) The dependency between evapotranspiration and the capillary stored water quantity.
(b) The relations between infiltration, capillary stored water quantity and deep perlocation.

The substrates to be used are individually composed and sowed with locally adapted turfgrass and kept in intensive culture with irrigation and fertilisation. Quantifying the functional dependencies in (a) is important, as the usable soil water storage capacity is usually a nonlinear function of the layer thickness. As vegetation layers are usually designed with locally available components, each one has its own functional dependencies.

Irrigating sports fields is necessary in longer dry periods during the main season. It forms therefore a major input to soil water. DFB [4] recommends irrigation intervals of 5..8 days and to detect the irrigation need by observing whether wilting starts. The total irrigation quantity should be between 20..25 l/m² for soccer playgrounds with a drainage layer, with a maximum hourly quantity of 5 l/m²/h.

2.4 Economical Assessment

Park, garden and sports facility planning, design and construction companies need to be capable to offer their customers best value for money. Value is usually pleasure in playing, composed by a number of qualitative factors. There are usually two types of costs in facility planning: non-recurring construction and recurring maintenance costs. The following paragraphs explain these cost categories for turfgrass soccer playgrounds.

2.4.1 Construction Costs

Construction work should be carried out with the most suitable materials and least effort as well as material usage. A major cost item when constructing sports grounds do form the materials for the substrate layer. The mixing process for the substrate can be carried out off-site at a quarry or at a compounding plant or on-site, e.g. with a wheel loader. The mixing recipe is usually defined and optimised, before construction starts. Hence, the material properties – and especially the usable water storage capacity – are analysed, beforehand.

In Germany, e.g. sands do usually cost 8..18 €/t free site; special substrates with higher water storage capacity cost between 20..100 €/t free site. Costs for special substrates can be reduced significantly by mixing them on-site, as transport costs for lightweight porous materials like lava and expanded clay are lower and freely available local topsoil can be used.

Material usage related construction labour and machinery costs do usually make up a much smaller share of material costs. They cover dredging and relocating the present soil, as well as transport, mixing and installation costs for the new substrate. As they are roughly proportional to the total substrate quantity, they can be combined with the material costs. Hence in this work, the substrate costs comprise both the material, machinery and labour costs. The substrate costs are relative to the necessary substrate quantity [€/t]:

$$Relative\ Substrate\ Costs = \frac{Material\ Costs + Machinery\ and\ Labour\ Costs}{Substrate\ Quantity} \quad (1)$$

$Depreciation\ costs$ form an economic approach for relating the one-off construction costs to costs per time period. Here, depreciation costs will be used to spread the construction costs over the usual usage time, leading to an annual "rent" for the sports ground. The usual usage time of sports grounds does vary considerably: Turfgrass on sportsgrounds in stadiums of soccer clubs the Germany's first federal league is often replaced twice a year because of special conditions, e.g. few light and wind as well as alternative forms of stadium usage, like e.g. rock concerts. Well-designed turfgrass sportsgrounds do have under correct course maintenance, usage and natural environmental conditions a life time that is only restricted by the lifetime of its technical components, like drainage tubes. Here, life times of 20..40 a are expected.

2.4.2 Maintenance Costs

Turfgrass sportsground maintenance costs – including e.g. mowing, scarifying, fertilising, sanding and rolling as well as irrigating – do make up about 30 €/m²/a in Germany. One component of the maintenance costs – the $irrigation\ costs$ – is principally reducible by design: providing more $usable\ soil\ water\ storage\ capacity$ should help the turfgrass overcoming longer dry periods. Tap water costs about 2.00 €/m³ in Germany [28], excluding sewage system costs. Therefore, minimising irrigation by design forms a well approach for saving costs.

2.5 Optimisation Approaches

2.5.1 Cost function

Optimisation objective is to find a cost minimum for the sum of a depreciation-based share of the $substrate\ costs$ and the $irrigation\ costs$ for given evapotranspiration and precipitation time series, the $overall\ annual\ costs$. $Irrigation\ costs$ are calculated by cumulating irrigation quantity over the simulation time period. The $substrate\ costs$ can be varied by adapting the $usable\ soil\ water\ storage\ capacity$ and therefore the $substrate\ layer\ thickness$ forming the vegetation layer. The turfgrass root depth does give a minimum limit for the substrate layer thickness.

$$Overall\ annual\ Costs = \frac{Irrigation\ Costs}{Simulation\ Duration} + \frac{Substrate\ Costs}{Depreciation\ Period} \quad (2)$$

With:

$$Substrate\ Costs = Relative\ Substrate\ Costs \cdot Layer\ Thickness \tag{3}$$

The cost function – the $overall\ annual\ costs$ – does only depend on one continuous variable: the $layer\ thickness$. The $overall\ annual\ costs$ are calculated after simulation runs. As irrigation events will be set and quantified by an algorithm during simulation[9], the cost function can be assumed to be non-continuous, probably with a couple of local minima. Hence, a metaheuristic optimisation approach should be chosen [29], [30].

2.5.2 Optimisation approach

Figure 2 shows a typical generic simulation-run based optimisation approach, mainly applied in non-linear programming.

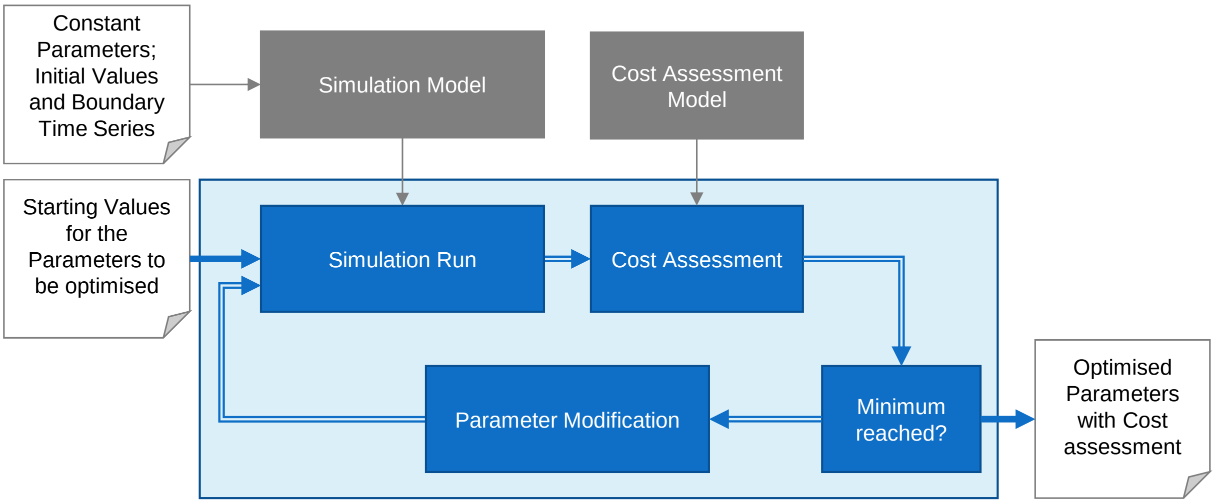

Figure 2: Simulation-run based Optimisation Approach

An optimisation task does basically have the following processing steps: The simulation model is pre-configured with constant parameters, initial values for the stocks and boundary time series. For given starting values and validity ranges for the parameters to be modified, the following loop is carried out by the optimisation routine: a simulation run of the chosen simulation model is executed. Then, a cost assessment by applying the cost function on the results of the simulation run is carried out, using the corresponding cost assessment model. In case that a global cost minimum in the search space for the parameters to be optimised is detected, the loop stops. Else, the optimisation routine carries out a modification of the parameters to be optimised and starts another simulation run.

3 Approach

3.1 General Specifications

A simulation run covers n discrete time steps $t_i = [0,1, \dots, t_i, \dots, t_n]$ with $t_i \in \mathbb{N}_0^+$ and the time increment $\Delta t = 1$ d. The current time step in a simulation run is available in the variable "$time$"[10].

3.2 Stock-Flow Model for Water Balance of Vegetation Layer Substrates

A simple linear soil balance model will be used, here, because:

- The main objective of this work is to showcase the methodology.

[9] Equations (5) and (6) in Table 2.
[10] The authors forego listing the usage of time in the stock-flow models for reasons of simplicity.

- Metaheuristic optimisation approaches do mainly rely on many model executions.
- Both excellent water infiltration[11] and high field capacity do form core properties of turfgrass substrate for soccer fields. However, the available precipitation and evapotranspiration input time series do only provide daily cumulated values for precitipation.

Therefore, the relations (b) will be modelled as simple balance equations, but with a maximum $usable\ capillary\ storage\ capacity$. Figure 3 presents the dependencies for simulation-based calculations of the cumulated irrigation quantity for given constants and boundary input values and a value for the $usable\ soil\ water\ storage\ capacity$. The notation applied in the model forms the System Dynamics stock-flow notation[12].

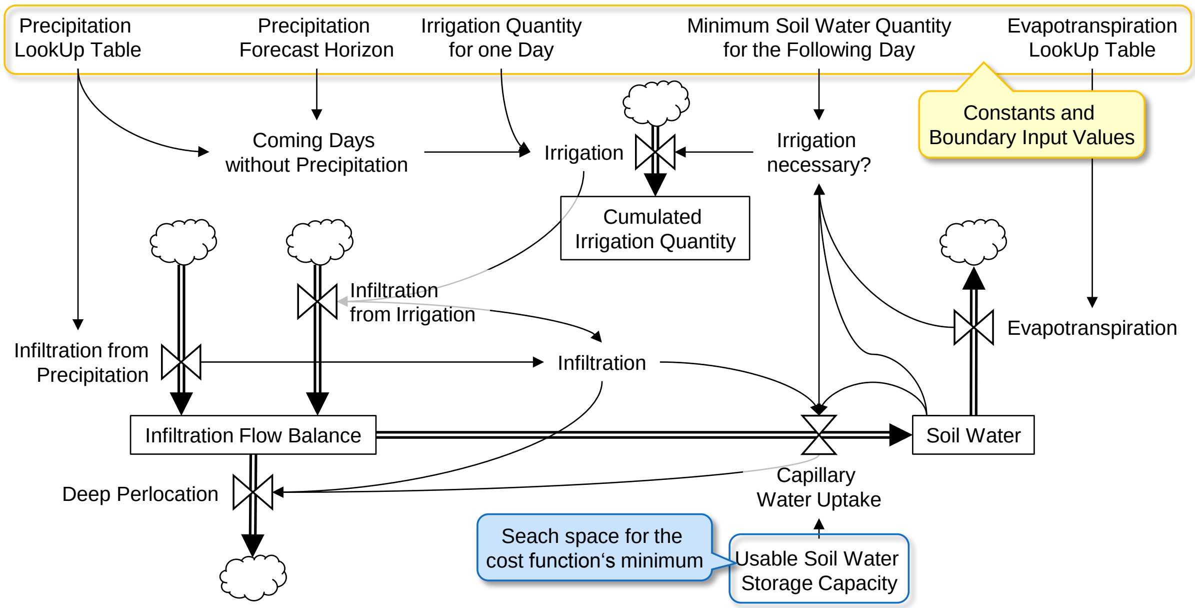

Figure 3: Stock-flow model of the water balance in a vegetation layer substrate

The values of stocks (generalised below as) x_i refer always to a given time point i. Here, the values of the flows Δx_i refer to the change in quantity between the time points $i-1$ and i. The current value of a stock x_i at the time point i is calculated by summating the flow balance Δx_i of the current time point i to the stock value x_{i-1} at the last time point[13]:

$$x_i = \max(x_{i-1} + \Delta x_i \cdot \Delta t; 0) \qquad (4)$$

[11] Typically ≥ 60 mm/h according to [5], p. 10, table 3.

[12] The main modelling entities do form stocks (state variables, boxed) that are connected with flows (double-lined arrows with valve symbols), representing their rates of change. Auxiliary variables (start and end points single-lined input/ information arrows) are used to calculate dependent values, whereas constants and lookup tables provide fixed scalar and vectorial data (starting point for input arrows). Sources and drains do represent state variables with an arbitrary, infinite value (represented as cloud symbols). Stock-flow models can be mapped directly on nonlinear differential equation systems. See e.g. [32], [33].

[13] The $\max(a_1; \dots; a_i; \dots; a_n)$ function returns the biggest of its arguments a_i. Here, its role in (4) forms restricting x_i to $x_i \in \mathbb{R}_0^+$.

The stock-flow model has the following constants and boundary input values:

Name	**Symbol**	**Value Type**	**Sample Value**	**Unit**
Precipitation LookUp Table[14]	PLT	Vector with n elements $\in \mathbb{R}_0^+$	$[0; 12.2.0; \dots 5.2]$	l/m²/d
Evapotranspiration LookUp Table[15]	ELT	Vector with n elements $\in \mathbb{R}_0^+$	$[1.5; 3.0; \dots 7.0]$	l/m²/d
Precipitation Forecast Horizon	PFH	$\mathbb{R}_0^+$	4.0	d
Irrigation Quantity for one Day	IQD	$\mathbb{R}_0^+$	5.0	l/m²/d
Minimum Soil Water Quantity for the Following Day[16]	MWQ	$\mathbb{R}_0^+$	5.0	l/m²/d
Usable Soil Water Storage Capacity[17]	SWC	$\mathbb{R}_0^+$	12.0	l/m²

Table 1: Constants and boundary input values in Figure 3

The provided sample values could correspond to a sandy substrate with a share of local soil, mixed on-site. The last constant in Table 1 needs to be varied when searching for the cost minimum.

The stock-flow model in Figure 3 has the following auxiliary variables[18]:

Name	**Symbol**	**Assignment**		**Unit**
Coming Days without Precitipation	$DWOP$	$= \sum_{n:=time+1}^{time+\mathrm{PFH}} \begin{cases} \mathrm{LookUp}(PLT, n) \equiv 0 & 1 \\ \text{else} & 0 \end{cases}$	(5)	d
Irrigation necessary?[19]	$IR?$	$= \begin{cases} SW_{i-1} + IFP_i - ET_i < MWQ & 1 \\ \text{else} & 0 \end{cases}$	(6)	–
Infiltration	INF	$= IFP + IFI$	(7)	l/m²/d

Table 2: Auxiliary variables in Figure 3

The next table features the flows:

Name	**Symbol**	**Assignment**		**Unit**
Irrigation	IRR	$= IR? \cdot IQD \cdot DWOP$	(8)	l/m²/d
Infiltration from Precipitation	IFP	$= \mathrm{LookUp}(PLT; time)$	(9)	l/m²/d
Infiltration from Irrigation	IFI	$= IRR$	(10)	l/m²/d
Capillary Water Uptake	CWU	$= \min(SWC - SW; INF)$	(11)	l/m²/d
Evapotranspiration	ET	$= \mathrm{LookUp}(ELT; time)$	(12)	l/m²/d
Deep Perlocation	DP	$= INF - CWU$	(13)	l/m²/d

Table 3: Flows in Figure 3

[14] A time series, obtained here from [11]. The unit l/m² is equivalent to mm.
[15] Ibidem.
[16] So that the turfgrass might start wilting, slightly.
[17] This constant is vegetation and substrate dependent; it represents how much consumable water in the soil is available to the plants under a specified care programme. The value varies with the substrate *layer thickness* and needs to be characterised, individually.
[18] The LookUp(vector, index) function returns the value of the element at the position index in vector.
[19] In the constraint of this conditional statement, an advance calculation of the soil water value SW_{i+1} for the *coming* day is carried out using SW_i, CWU_i and ET_i. SW_{i+1} is compared to the minimum soil water quantity for the following day MWQ.

The used assignment for calculating the irrigation quantity IRR is quite simple: although precipitation forecasts are quite reliable in terms of their start and duration for broader areas, precipitation quantities may vary, locally. Therefore, a simple approach basing on counting the coming dry days was chosen, here.

The succeeding table lists the stocks together with their flow balances:

Name	Symbol	Assignment		Initial Value	Unit
Infiltration Flow Balance[20]	IFB	$\Delta IFB = +IFP + IFI - DP - CWU$	(14)	0	l/m²
Soil Water[21]	SW	$\Delta SW = +CWU - ET$	(15)	e.g. $SWC/2$	l/m²
Cumulated Irrigation Quantity[22]	CIQ	$\Delta CIQ = +IRR$	(16)	0	l/m²

Table 4: Stocks in Figure 3 with Flow Balance Equations

3.3 Assessing Costs of Simulation Runs

After running simulations, the total costs for the current model configuration are calculated. This is carried out in function of the Cumulated Irrigation Quantity CIQ [l/m²] and the Usable Soil Water Storage Capacity SWC [l/m²]. The substrate $Layer\ Thickness$ is calculated, additionally, for easier comparisons with other soccer playground design models[23]. The following figure shows the stock-flow model for the economical assessment of a simulation run.

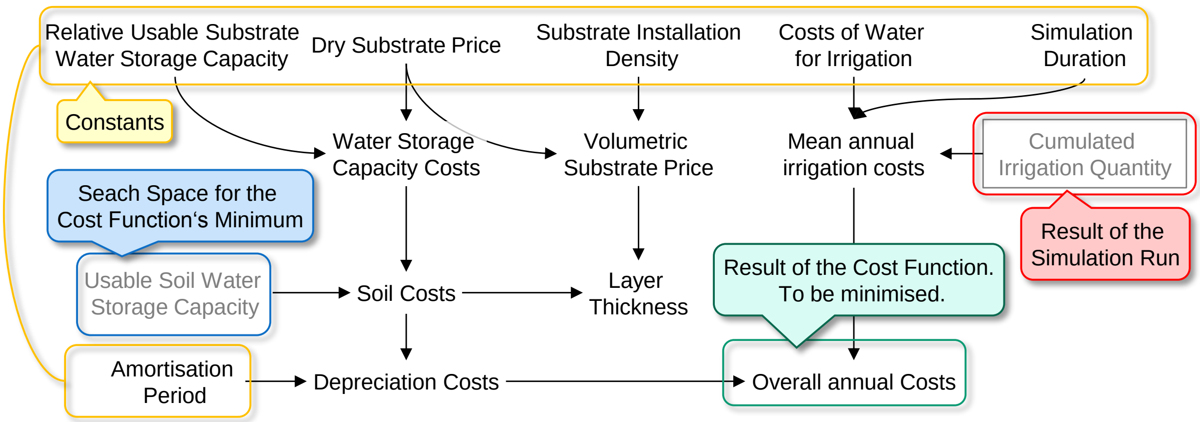

Figure 4: Stock-Flow Model for the Economical Assessment of a Simulation Run[24]

The overall annual costs do form the sum of the depreciation costs for the substrate and the mean annual irrigation costs. The following two tables do list the constants and auxiliary variables in Figure 4.

[20] The soil water balance was split here in the Infiltration Flow Balance and the Soil Water stock. The latter is fed by capillary water uptake, only. As any water that is not stored in the soil's capillaries goes into Deep Perlocation, the Infiltration Flow Balance stays 0, always.
[21] As the initial value for this stock is unknown, it is estimated as half of the soil water capacity. Resulting errors are negligible, as $SWC \ll \sum_{i=0}^{n} ET_i$.
[22] This stock was introduced for calculating the total irrigation costs after a simulation is finished.
[23] See section 2.1.
[24] Modelling entities already defined in the stock-flow model in Figure 3 are set in grey.

Name	Symbol	Value Type	Sample Value	Unit
Relative Usable Substrate Water Storage Capacity[25]	$SWSC$	$\mathbb{R}_0^+ \cap [0..1]$	0.12	100 %
Dry Substrate Price	DSP	$\mathbb{R}_0^+$	18.00	€/t
Substrate Installation Density[26]	SID	$\mathbb{R}_0^+$	1.4	t/m³
Costs of Water for Irrigation	CWI	$\mathbb{R}_0^+$	2.00	€/m³
Simulation Duration[27]	SD	$\mathbb{R}_0^+$	1	a
Depreciation Period	AP	$\mathbb{R}_0^+$	30	a

Table 5: Constants in Figure 4

Name	Symbol	Assignment		Unit
Mean annual Irrigation Costs	$MAIC$	$= \frac{CIQ}{1{,}000} \cdot \frac{CWI}{SD}$	(17)	€/m²/a
Water Storage Capacity Costs[28]	$WSCC$	$= \frac{DSP}{SWSC \cdot 1{,}000}$	(18)	€/(l/m²)/m²
Volumetric Substrate Price	VSP	$= DSP \cdot SID$	(19)	€/m³
Soil Costs	SC	$= WSCC \cdot SWC$	(20)	€/m²
Layer Thickness	LT	$= \frac{SC}{VSP} \cdot 1{,}000$	(21)	Mm
Depreciation Costs	DC	$= \frac{SC}{AP}$	(22)	€/m²/a
Overall annual Costs	OAC	$= MAIC + DC$	(23)	€/m²/a

Table 6: Auxiliary Variables for the Economical Assessment of a Simulation Run

The minimum layer thickness $LT_{min} = 80$ mm in section 2.1 forms as well the lower border of the search space – the usable soil water storage capacity SWC. The following equations calculate its lower border SWC_{min}, using dependencies (20) and (21) in Table 6:

$$SWC_{min} = \frac{LT_{min}}{1{,}000} \cdot \frac{VSP}{WSCC} \tag{24}$$

Inserting equation (19) for the volumetric substrate price VSP and equation (18) for the water storage capacity costs $WSCC$ into equation (24) leads to the following relation[29] for SWC_{min}:

$$SWC_{min} = LT_{min} \cdot SID \cdot SWSC \tag{25}$$

A rule of thumb is that the rooting depth of periodically cut turfgrass follows the cutting thickness. In case that turfgrass growth tests on the substrate show a lower rooting depth, LT_{min} can be adapted.

The maximum layer thickness LT_{max} or usable water storage capacity SWC_{max} should be set intuitively experience-based: optimisation runs with a too low value will result in the given maximum value as an “optimal” one. Clearly too high values will lead to increased computation times, as the search space is much wider than necessary.

[25] The value is a mass percentage with the unit m³ Water / t dry substrate = %; the multiplication factor 100 in the Unit column compensates the percentage fraction of $1/100$.
[26] In installed conditions.
[27] Overall length of the time series taken as a basis.
[28] Unit conversion using 1 $m^3_{H_2O} = 1{,}000$ l and the expansion term $1 = \frac{m^2}{m^2}$: $\frac{€}{t} \cdot \frac{t}{1{,}000\,l} \cdot \frac{m^2}{m^2} = \frac{1}{1000} \cdot \frac{€}{(l/m^2) \cdot m^2}$
[29] Unit conversion (see footnote 28): mm$\cdot \frac{t}{m^3} \cdot \frac{1\,m^3_{H_2O}}{t} = \frac{m}{1{,}000} \cdot \frac{t}{m^3} \cdot \frac{1{,}000\,l}{t} = \frac{l}{m^2}$

3.4 Optimisation Approach

The model in sections 3.2 and 3.3 was programmed in Microsoft Excel® 2010[30]. For minimising the *Overall Annual Costs* in function of the *Usable Soil Water Storage Capacity*, the optimisation algorithm of the Evolutionary Solver of the Microsoft Excel® Solver Add-In [35] was used.

3.5 Exemplary Optimisation Results

After demonstrating the optimisation approach for one season at one location, optimisation results for six locations with typical local weathering in Germany using time series covering 25 a are shown. Then, a sensitivity analysis for the overall annual costs in function of the length of the depreciation period and the substrate layer thickness is carried out.

3.5.1 Time Series for one Season

The first example features the soil water balance for a turfgrass sportsground nearby Stuttgart airport[31] during the main season 2017 for a soil water storage capacity of 25 l/m², corresponding to a substrate layer thickness of 148.8 mm. The cumulated potential evapotranspiration over grass and sandy loam in the season is 592.0 l/m²/season, whereas precipitation amounts to 466.3 l/m²/season. The used parameterisation is the one indicated in Table 1 and Table 5.

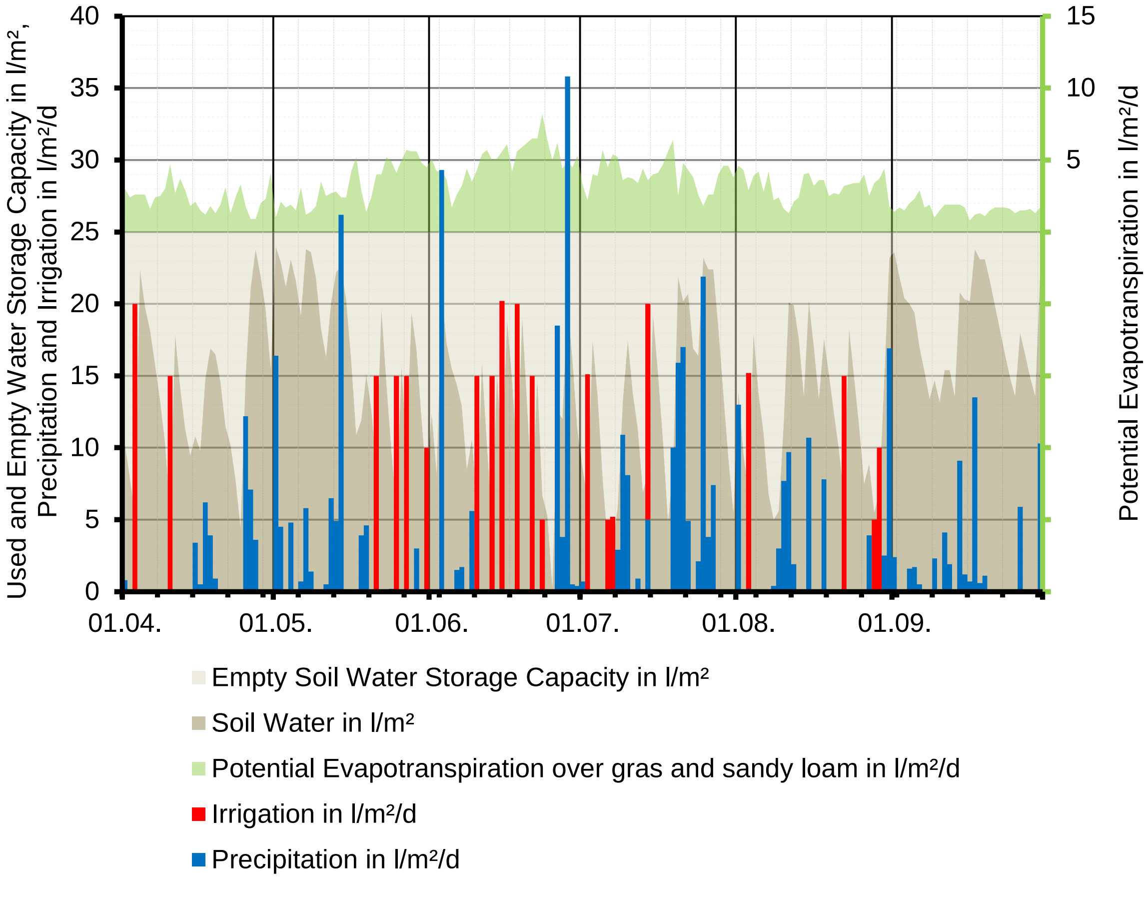

Figure 5: Simulated Soil Water Balance on a Turfgrass Soccer Playground in Stuttgart-Echterdingen in the main season 2017, with a Soil Water Storage Capacity of 25 l/m², without Optimisation

[30] There are quite better software environment choices for implementing the simulation and the cost model, as input and output data, the models and its documentation should be maintained, separately – especially in Decision Support Systems. Here, Microsoft Excel® 2010 was chosen to keep the barriers to entry on a simple level for planners and designers.

[31] For the time series, see [11]. The weather station identifier is 4931, Stuttgart-Echterdingen, latitude 48.69 °, longtitude 9.22 °. The values of VPGB and RSK between 01/04/2017-30/09/2017 were used.

Using the formulas in section 3.2, 20 irrigation events with a cumulated irrigation quantity of 265.0 l/m² are happening in the simulated season. Figure 5 shows the corresponding time series, with longer irrigation periods at the end of May and in June. The estimated overall annual costs with this configuration are 0.655 €/m²/a.

	Solver algorithm applied	Soil Water Storage Capacity	Soil Layer Thickness	Mean annual Irrigation Costs	Overall annual Costs
Original Parametrisation	–	25.0	148.8	0.53	0.655
	GRG Nonlinear[32]	24.4	145.2	0.52	0.642
	EA (Evolutionary Algorithm)[33]	50.1	298.2	0.29	0.541
Unit		l/m²	mm	€/m²/a	€/m²/a

Table 7: Comparison of the Optimisation Results for simulated Irrigation on a turfgrass Soccer Playground in Stuttgart-Echterdingen in the main season 2017

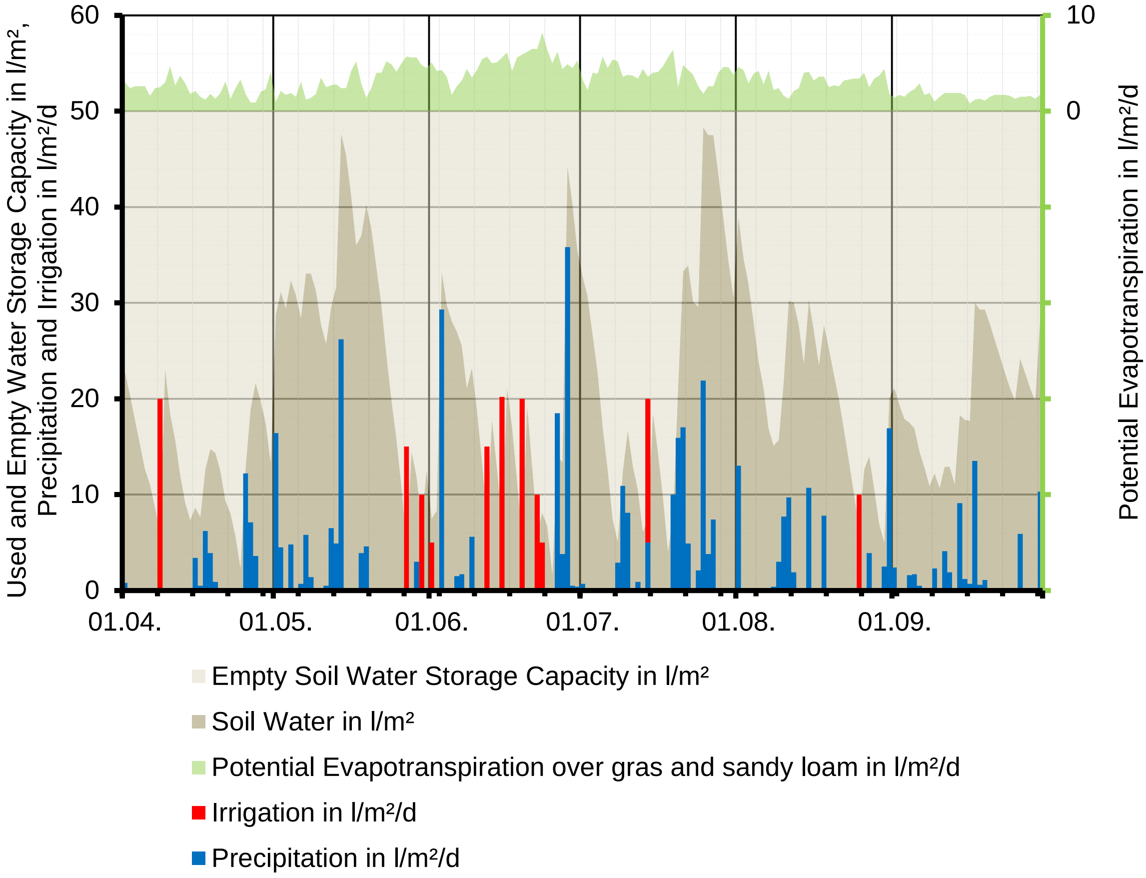

Figure 6: Simulated Soil Water Balance on a Turfgrass Soccer Playground in Stuttgart-Echterdingen in the main season 2017 with a Soil Water Storage Capacity of 50.1 l/m², after Optimisation

[32] [35] states that this „*method for nonlinear optimization uses the Generalized Reduced Gradient (GRG2) code, which was developed by Leon Lasdon, University of Texas at Austin, and Alan Waren, Cleveland State University, and enhanced by Frontline Systems, Inc.*".

[33] [35] writes that this "*method for non-smooth optimization uses a variety of genetic algorithm and local search methods, implemented by several individuals at Frontline Systems, Inc.*"

Figure 6 shows same the simulated soil water balance – but with an optimised usable soil water storage capacity, using the EA algorithm of the Excel® solver: The soil water storage capacity got increased to 50.1 l/m², whereas the overall annual costs got reduced to 0.541 €/m²/a. The number of irrigation events got reduced to eleven with a total quantity of 145 l/m². The overall annual costs are reduced by 17.4 % to 0.541 €/m²/a, although the substrate layer thickness gets rather doubled. Substrates with an improved water storage capacity could lead to a reduced suggested soil layer thickness, here. It can be seen that only about 40 % of the available spoil water storage capacity are getting replenished by irrigation. The huge soil water storage capacity of 50.1 l/m² is used now to store precipitation in longer wet periods in order to overcome drier periods, better. Hence, less water is lost via deep perlocation.

Table 7 compares the optimisation results after applying the two principally eligible Excel® solver algorithms [35]. Table 7 shows that the evolutionary algorithm performs much better, as the cost function is a non-continuous one because of the algorithm-triggered irrigation events.

3.5.2 Time Series covering multiple Seasons

Weathering conditions tend to vary locally and annually, considerably. Hence, time series covering local weathering during multiple seasons should be used as a basis for optimising usable soil water storage capacity.

Table 8 and Table 9 compare long-term optimisation runs for six weather stations in Germany [11], chosen for their specific local weathering conditions. All time series cover 25 a with in total 9,497 values from 01/01/1992 to 31/12/2017. Optimisations were carried out with depreciation periods of 10 and 30 years. As before, the used parameterisation is the one indicated in Table 1 and Table 5.

For each location, the following tasks were carried out[34]: First, the costs were calculated for a depreciation period of 10 a and a standard soil layer thickness of 120 mm for designs with a drainage layer (see section 2.1). Then, the optimisation was carried out. Finally, the depreciation period was increased to 30 a and again, an optimisation was carried out.

Without optimisation, the model calculates for the 10 a depreciation period overall annual costs for all locations between 0.554 €/m²/a for the cool and mostly wet town Garmisch-Partenkirchen and 1.090 €/m²/a for the dry region around Manschnow, nearby the Polish border (see Table 8). The overall annual costs for the even drier town Bernburg/Saale (Nord) amount to nearly the same as for Manschnow.

By optimisation for a 10 a depreciation period, all soil layer thicknesses got increased to values between 153 and 159 mm, except the one for the Alps town Garmisch-Partenkirchen with 133 mm soil layer thickness. After optimisation, there are for all locations considerable irrigation cost savings. There are reductions of the overall annual costs for all locations, the smallest one for Garmisch-Partenkirchen, the biggest ones for Stuttgart-Echterdingen and Bernburg/Saale (Nord).

In the optimised cases with a 30 a depreciation period, the soil layer thickness gets increased further for all cases, but its values tend to differ more, possibly because local weathering conditions like longer dry and wet periods or occasional heavy rainfalls are getting more important: the smallest is 198 mm in Manschnow, the biggest one 246 mm in Stuttgart Echterdingen. For the mountain town Garmisch-Partenkirchen, a soil layer thickness of 208 mm is calculated. This could be due to longer sunny and dry periods, caused by foehn winds crossing the Alps from South to North.

Table 9 compares the optimised soil water storage capacity and the optimised overall costs for depreciation periods of 10 a and 30 a. Except for Garmisch-Partenkirchen, the soil water storage capacity is ~29..59 % bigger for 30 a depreciation periods. For 30 a depreciation periods, overall annual costs are getting reduced by 28..52 %. Therefore, designing for the long term seems to be quite important although construction costs might be higher. The case for Garmisch-Partenkirchen is an interesting one, as already mentioned, above: For 30 a depreciation periods, the optimised soil layer storage capacity is quite comparable to the ones for Hamburg-Neuwiedenthal/ Frankfurt/Main-Westend and Manschnow. This indicates that time series with typical local weathering could be more important than mean annual precipitation for vegetation layer design for a given location.

[34] The results of each task are listed in their corresponding results column.

Name	**Stuttgart-Echterdingen**			**Bernburg/Saale (Nord)**			**Hamburg-Neuwiedenthal**			**Unit**
CDC Station ID	4931			445			1981			–
Latitude	48.6883			51.8218			53.4777			°
Longitude	9.2235			11.7109			9.8957			°
Height over Standard Elevation Zero[35]	371			84			3			m
Climate classification[36]	Temperate oceanic (Cfb)			Temperate continental (Dfb)			Coastal temperate oceanic (Dfb)			–
Mean annual Precipitation[37]	727.4			489.6			794.7			mm/a
Mean temperature[38]	9.93			9.44			9.70			°C
Optimised?	–	✓	✓	–	✓	✓	–	✓	✓	–
Depreciation Period	10	10	30	10	10	30	10	10	30	a
Soil Water Storage Capacity	20.2	25.9	41.3	20.2	26.7	40.4	20.2	26.1	36.4	l/m²
Substrate Layer Thickness	120	154	246	120	159	241	120	155	216	mm
Mean annual Irrigation Costs	0.706	0.516	0.386	0.780	0.584	0.497	0.522	0.384	0.310	€/m²/a
Overall annual Costs	1.008	0.905	0.593	1.082	0.984	0.699	0.824	0.776	0.492	€/m²/a

Name	**Frankfurt/Main-Westend**			**Garmisch-Partenkirchen**			**Manschnow[39]**			**Unit**
CDC Station ID	1424			1550			3158			–
Latitude	50.1269			47.4831			52.5468			°
Longitude	8.6694			11.0623			14.5452			°
Height over Standard Elevation Zero	124			719			12			m
Climate classification	Warmer temperate oceanic (Dfb)			Cool continental (Dfc), North side of the Alps			Temperate continental (Dfb)			–
Mean annual Precipitation	640.1			1,301.0			512.1			mm/a
Mean temperature	11.35			7.52			9.61			°C
Optimised?	–	✓	✓	–	✓	✓	–	✓	✓	–
Depreciation Period	10	10	30	10	10	30	10	10	30	a
Soil Water Storage Capacity	20.2	26.6	34.2	20.2	22.4	34.9	20.2	25.6	33.2	l/m²
Substrate Layer Thickness	120	159	203	120	133	208	120	153	198	mm
Mean annual Irrigation Costs	0.694	0.513	0.458	0.252	0.196	0.081	0.788	0.616	0.556	€/m²/a
Overall annual Costs	0.996	0.912	0.629	0.554	0.532	0.255	1.090	1.001	0.722	€/m²/a

Table 8: Optimisation Results for simulated Irrigation on a Turfgrass Soccer Playground at various Locations in Germany from 1992 to 2017 with depreciation periods of 10 and 30 a

[35] Standard Elevation Zero of the German Mean Height Reference System.

[36] According to Klöppen-Geiger. See [36], adapted. [37], p54 provides a more detailed climate zone segmentation for Germany into 22 classes with comparable precipitation and months of growth; see [38]. The top-left map in [37], p55 suggests considering as well areas tempered by sea breezes and with Föhn influence (dry winds from the south over the Alps). [Sic!] The input data for ibidem, p54 is for the years 1961-1990 and hence does not reflect climate change in the last 27 years.

[37] Calculated from the RSK daily precipitation time series data.

[38] During the period of the time series. Calculated on basis of the TMK daily mean temperature time series data.

[39] Mean annual precipitation and mean temperature: Missing RSK and TMK values were substituted with the mean of the present ones. This was carried out for 39 RSK and 16 TMK of 9,497 total values.

Station Name (CDC Station ID)	Mean Annual Precipitation	Mean Temperature	Optimised Soil Water Storage Capacity with 10 a depreciation period	Optimised Soil Water Storage Capacity with 30 a depreciation period	Optimised Overall Costs with 10 a Depreciation Period	Optimised Overall Costs with 30 a Depreciation Period
Bernburg/Saale (Nord) (445)	489,6	9,44	26,7	40,4	0,984	0,699
Manschnow (3158)	512,1	9,61	25,6	33,2	1,001	0,722
Frankfurt/Main-Westend (1424)	640,1	11,35	26,6	34,2	0,912	0,629
Stuttgart-Echterdingen (4931)	727,4	9,93	25,9	41,3	0,905	0,593
Hamburg-Neuwiedenthal (1981)	794,7	9,7	26,1	36,4	0,776	0,492
Garmisch-Partenkirchen (1550)	1301,0	7,52	22,4	34,9	0,532	0,255
	l/m²/a	°C	l/m²	l/m²	€/m²/a	€/m²/a

Table 9: Optimisation Results for simulated Irrigation on a Turfgrass Soccer Playground at various Locations in Germany from 1992 to 2017 with depreciation periods of 10 and 30 a

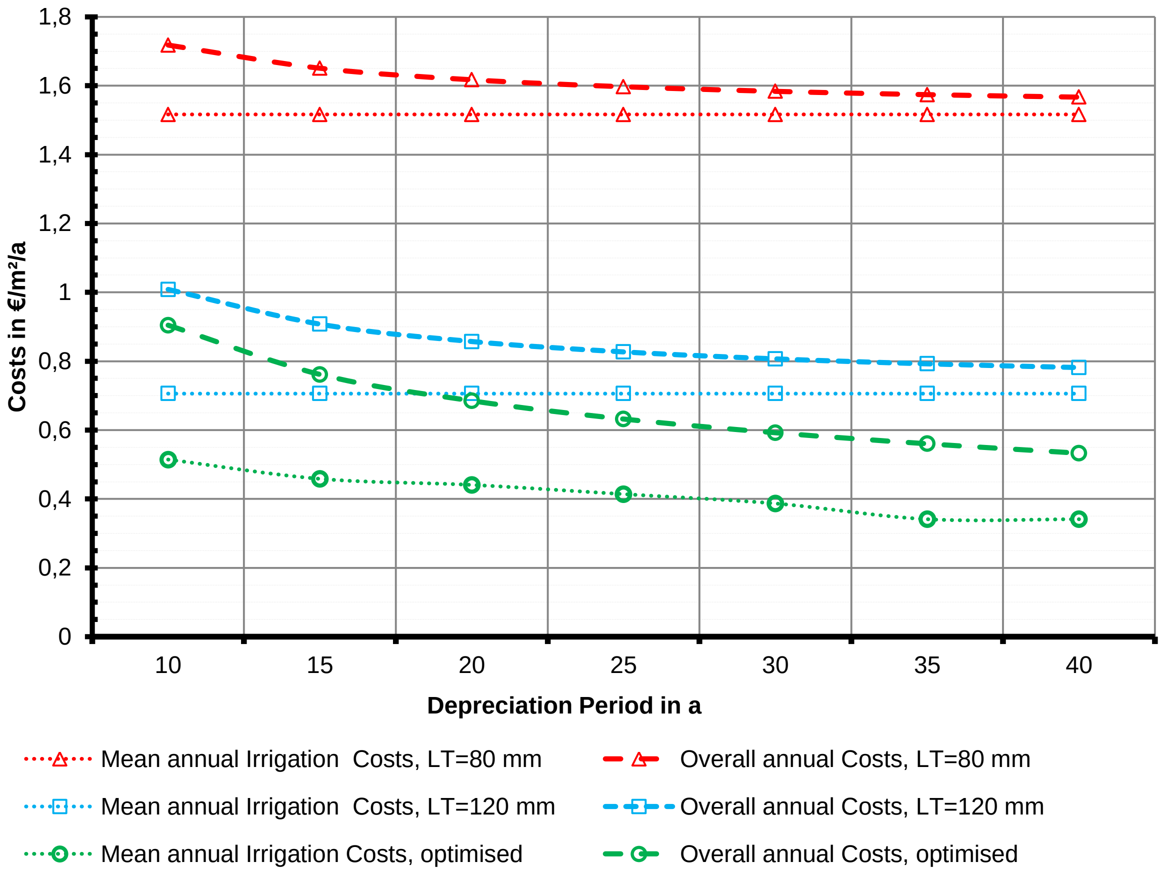

Figure 7: Sensitivity Analysis for Overall Annual Costs as a Function of the Depreciation Period for a Turfgrass Soccer Playground with standard and optimised soil layer height in Stuttgart-Echterdingen, from 1992 to 2017

3.5.3 Sensitivity Analysis: Depreciation Period and Substrate Layer Thickness

Figure 7 shows the influence of the depreciation period length on the mean annual irrigation costs and the overall annual costs with standard[40] and optimised substrate layer thicknesses for Stuttgart-Echterdingen for a simulated time span from 1992 to 2017.

The mean annual irrigation costs with a soil layer thickness of 80 mm do amount 295 % of the corresponding ones for an optimised layer thickness with a depreciation period of 10 a. With a depreciation period of 30 a, this percentage rises to 392 % and to 444 % for a depreciation period of 40 a. Irrigation costs for a substrate layer thickness of 120 mm are quite more favourable than for a layer thickness with 80 mm, but are still 137..207 % of the ones for an optimised substrate layer thickness.

For the cases with optimised soil layer thicknesses, it can be seen that the mean annual irrigation costs are dropping with longer depreciation periods: there are cost savings of 33.7 % between the case with a depreciation period of 10 years and the cases with depreciation periods of 35 and 40 a. The overall annual costs drop by 41.1 %, when comparing the 10 a depreciation period case to the one with 40 a. The overall annual costs of 1.57 €/m²/a with an 80 mm substrate layer thickness for a depreciation period of 40 a do form 294 % of the ones with an optimised substrate layer thickness.

Hence, an optimised substrate layer thickness is both recommendable for keeping costs down for short and long depreciation periods, here.

4 Discussion

After categorising the presented approach in decision support research, the modelling approach is being discussed. The following section showcases relevant aspects for key stakeholders.

4.1 Categorisation of this Approach in Decision Support System Research

Power (2001) [39] suggests defining decision support systems "*as a broad category of information systems for informing and supporting decision makers*" with the intention "*to improve and speed up the processes by which people make and communicate decisions*"[41]. They feature "*mathematical-analytical models as major component*" and rely on "*choosing the appropriate model as key design issue*"[42]. The presented approach does neither feature a software implementation nor an information system, but a supporting method – to be implemented and provided in an executable form for decision makers intending to improve decision quality and certainty by "*making sense of structured data*"[43]. According to the criteria of Power (2001), the method can be seen as a model-driven one, using "*data and parameters provided by decision makers to aid them in analysing a situation*"[44] that is function-specific, as it helps accomplishing a specific task.

4.2 Modelling approach

The used model relies on measured precipitation and estimated potential evapotranspiration time series. The stock-flow model for the soil water balance is kept quite simple and does not include functional dependencies between soil layer thickness and capillary water storage capacity. Hence, for analyses for a given location of a soccer field, it is necessary to rely on water balances for a specified substrate with a chosen turfgrass type under well-approved soccer sportsground maintenance, e.g. captured by a lysimeter. The core behaviour of this water balance model could be approximated by non-linear regression models, covering functional dependencies for e.g. capillary water uptake, usable soil water storage capacity in function of substrate layer height and evapotranspiration.

[40] The standard soil layer height of 80 mm corresponds to a soil water storage capacity of 13.4 l/m²; the standard soil layer height of 120 mm corresponds to a soil water storage capacity of 20.2 l/m².
[41] [39], p432.
[42] Ibidem, p436.
[43] Ibidem, pp435.
[44] Ibidem, p433.

Field capacity is a well-defined measure[45] for the upper limit of available water to plants. Its characterisation for the approach in this contribution needs to be carried out at with substrate at installation density and well-grown turfgrass on it. The other relevant parameter for calculating the usable soil water storage capacity is here the not the permanent, but the starting point for wilting of turfgrass, as drought stress should be avoided. Hence, this parameter is an observation-based one – and therefore, the usable soil water storage capacity, as well.

The irrigation instructions in this work are for DFB soccer sportsgrounds with layer thicknesses of 80..120 mm and hence for usable water storage capacities of approximately 13..20 l/m². For depreciation periods of 30 years, the optimisation algorithm suggests much higher water storage capacities, between 33.3 and 41.4 l/m² for the locations in Table 8. Therefore, the following constants could be varied as well by the optimisation algorithm: the irrigation quantity for one day and the precipitation forecast horizon.

4.3 Relevant Aspects for Key Stakeholder Groups

The following aspects are relevant for key stakeholders in Germany. They should be mostly transferable to other countries with similar semi-humid and humid temperate climate.

4.3.1 Substrate Providers for Turfgrass Sportsgrounds

Using substrates with a superior usable soil water storage capacity could be an alternative to avoid higher substrate layers. Such substrates might be composed e.g. with shares of porous aggregates like lava. In order to keep the transport cost share low, on-site mixing could be considered, as porous aggregates can be comparatively lightweight.

4.3.2 Turfgrass Sportsground Planning and Construction Companies

The presented method permits finding a cost optimum for substrate costs and irrigation costs in a given depreciation period under local weathering conditions. The presented approach needs to be adapted to local construction and substrate costs.

4.3.3 Sports Clubs and Municipal Bodies as Sportsground Owners

The results of this contribution show that irrigation costs do clearly go in function of sportsground design. Hence, call for tenders for turfgrass sportsgrounds should explicitly ask for resulting irrigation costs, taking local weathering conditions into account. This might lead to increased construction costs, but to considerable savings on the long term. Modern turfgrass sportsground substrates and design do come as well with quite good water discharge for heavy rain and cloudbursts and do hence permit extended usage times and therefore lower costs per usage hour.

5 Conclusions

Although the presented work still comes with a number of uncertainty factors, it shows that the simulation-based technical design of turfgrass soccer playgrounds comes with a significant improvement potential with respect to finding an economical optimum between construction and irrigation costs. The presented methodology relies on publicly available data and was implemented in Microsoft® Excel. Hence, it could be easily adopted by sportsground planners.

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