A Data-integrated and Performance-oriented Parametric Design Process for Terraced Vineyards

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Abstract: Recovery of land knowledge can help to advance the understanding of socio-ecological systems like traditional sustainable agricultural systems. Such efforts require transdisciplinary inquiry, data acquisition and analysis, as well as the development of data-integrated design processes for implementing recovered knowledge in the design of such systems. This article describes the development of a framework for a data-integrated performance-oriented computational design process for the selected case of high-altitude terraced vineyards in Lamole, Tuscany. Based on interviews with local farmers that work with the traditional system of high-altitude terraced viticulture, this research involved analysis of the most complete terraced vineyard in this location, leading to the definition of a performance metric and the development of a parametric computational design process that constitutes a first step towards a generative design approach to terraced vineyards.

Keywords: Data-integrated design, parametric design process, computational terrain modelling, geospatial analysis, terraced vineyards

1 Introduction

Socio-ecological systems like traditional sustainable agricultural systems can offer valuable insights for advancing sustainable planning and design. This includes recovery of traditional land knowledge involving terrain manipulation, construction and agricultural practices that are well attuned to their context and climate. One interesting example is agricultural terraced landscapes that exist in diverse cultural and climatic contexts (VAROTTO et al. 2019). Well-maintained terraced landscapes support habitat diversity, soil health and landscape complexity (BRUNORI et al. 2020). They prevent soil erosion (NAPOLI et al. 2020), negative impact of water runoff and sediment transport in sub-catchment scale (BAI et al. 2019). Terraced landscapes are widely diffused in Mediterranean Europe, where viticulture is a particularly important socio-economic resource (BONARDI 2019). We focused on high-altitude viticulture with traditional terraced vineyards in Lamole, Tuscany, and their capacity for advantageous microclimatic modulation. (HENSEL et al. 2018, TUCCI et al. 2019, PARISI & TYC 2020, TYC et al. 2021). In Lamole, the study of the criteria that govern vineyard layouts benefits from the presence of vineyard owners who are familiar with the traditional method of terraced

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vineyard cultivation from before the 1970s when land abandonment and industrialization of viticulture led to major changes in the way vine was cultivated and produced. This makes it possible to directly obtain insights from practitioners that know how terraced vineyards were laid out and operated prior to the 1970s. Furthermore, it is possible to better understand adaptations of terraced vineyards to changing conditions or technological advancements. In recent years we conducted numerous interviews with vineyard owners to record this knowledge.

Recently two new terraced vineyards were reconstructed in Lamole, which indicates renewed interest in traditional viticulture and the related vineyard typology. Given this interest, we found it useful to develop a design method for this typology. This entailed a data-integrated and performance-oriented computational design processes for generating terraced vineyard layouts. For the design process we utilized data collected in various surveys, as well as data derived from geospatial simulations. We then defined performance metrics related to environmental metrics, construction, and operation of terraced vineyards that can inform a generative design process and deliver benchmarks for performance evaluation of the different design outputs.

Computational design methods in landscape architecture can be informed by data obtained through surveys (WALLISS & RAHMANN 2016a), simulations, (WALLISS & RAHMANN 2016b), and by parameters related to construction and mechanized earthworks processes (JUD et al. 2021) that enable precise terrain modifications. These technological advancements are reflected in planning methods (HURKXKENS & BERNHARD 2019) that support large scale land modifications. However, reconstruction or design of new terraced vineyards is commonly based on rough planning and decisions directly taken on site during the process of construction. Existing methods typically consider widths and counts of terraces, walls and embankments (SHAO et al. 2013, BAY et al. 2014, BERČIČ & AŽMAN-MOMIRSKI 2020). However, the link between the specific vineyard layout and features and environmental performance is not commonly based on and elaborated by data-integrated computational design processes. The research presented in this article seeks to address this gap and portrays the development of a framework for a data-integrated performance-oriented computational design process for terraced vineyards. This is pursued through research by design methodology (HAUBERG 2011) and includes analytical methods to gain better understanding of the relation between layout and geometry of a vineyard and its related environmental performance (TYC et al. 2021). The research challenge lies in recovering and translating vernacular land knowledge into an instrumental design process that can be implemented in similar contexts or adapted to different contexts. We selected a vineyard (Grospoli I) for analysis that represents the most complete existing terraced vineyard and related water management system in Lamole. This study focused on the scale of the vineyard and the territorial scale of the Lamole valley and integrates geospatial data and simulation tools to configure a computational workflow. In follow-up research it is intended to extend this into an interactive computational workflow combined with targeted design decision support.

Traditional viticulture utilizes numerous means to produce high quality wine, such as mixing grapes from different locations. This introduces a logic that is at odds with contemporary optimization approaches in design that would suggest the design of a vineyard that is inherently optimal. For this reason, we focused on principle aspects that can be analysed, parametrically defined, and inform designs to ensure resilient performance under a range of conditions. A generative computational design process might therefore result in various design outputs that all fulfil pre-set requirements. Nevertheless, to understand even apparently minute differences can yield new insights, as well as deliver evidence requested by subsidy granting authorities that support local farmers. Thus, the design process needs to focus on the performance across a range of conditions, instead of a single optimised output.

2 Materials and Methods

2.1 General Methods Employed in this Study

This study uses research by design methodology as proposed by HAUBERG (2011), which assumes that design can lead to new insights, knowledge, and innovative practices. It follows a nomothetic approach, where research arises from the design process, through generalization and rationalization, and combines systematic and expressive inquiry, establishing a direct link between analysis and architectural proposal. Furthermore, this research builds on multimodal data acquisition, combining geoscientific analysis, geodata processing and a generative computational design process.

2.2 Data Sources Used in this Study

This study used geospatial data collected from 2017 to 2020 in Lamole, Tuscany. The airborne survey of the whole Lamole valley was acquired by Servizi di Informazione Territoriale (S.I.T.) s.r.l. of Bari (Italy) on 6 August 2020. The dataset referred to as "territorial scale", includes point cloud data produced by LiDAR in 0.5 m resolution, as well as a Digital Terrain Model (DTM) and a Digital Surface Model (DSM). Images collected during the same flight were used to generate an orthophoto covering the whole Lamole valley in 6-7 cm resolution. UAV photogrammetric data describing the vineyard Gropoli I (see Section 3.2) in 2 cm resolution referred to as "site scale" was collected in 2017 by TUCCI et al. (2019). Open-access land use data was retrieved from Geoscopio Portal of Regione Toscana in 2021. Diverse surveys were conducted in Lamole and Grospoli I vineyard (TUCCI et al. 2019, PRETI et al. 2018, SANTORO et al. 2020). This publication portrays a full trajectory towards a design process, building up on previous survey activities (TUCCI et al. 2019) and data analysis and integration methods (TYC et al. 2021).

Table 1: Main properties of the geospatial datasets used in this study

	Airborne LiDAR	**Airborne RGB**	**Grospoli I UAV Photogrammetry**
Spatial resolution	50 cm (GSD)	6-7 cm (GSD)	2cm (GSD)
Area covered	Lamole valley 341 ha	Lamole valley 341 ha	Grospoli I vineyard 1.8 ha
Available data products	Digital Terrain Model Digital Surface Model Classified point cloud	Orthophoto	Unclassified point cloud Orthophoto
Platform	Vulcanair P68 B Riegl LMS-Q680i	Vulcanair P68 B Phase One iXU-RS-1000	DJI Phantom 4 Pro
Acquisition date	6 August 2020	6 August 2020	7 September 2017

2.2 Computational Methods

The data-integration method and related simulation tools used in this study extend a framework referred to as *Composite Voxel Model* (TYC et al. 2021). Solar radiation analysis was calculated using the Potential Incoming Solar Radiation component HOFIERKA et al. (2002) in SAGA GIS 7.9.0 (CONRAD et al. 2015). Rhinoceros 3D and Grasshopper is a widely adopted software package for parametric design that is frequently applied in the field of digital landscape architecture (BELESKY 2018). Some Grasshopper plugins incorporate raster based geospatial datasets, including Docofossor (HURKXKENS & BERNHARD 2019), Ibex (HELLER 2020) or ShrimpGIS (DI NUNZIO 2020). Numerous studies utilizing three dimensional, geospatial datasets within Rhinoceros 3D have been reported (YIJING & YUNING 2018, URECH 2019). However, such studies often require proficiency related to wide range of hardware and software and creation of interfaces to enable interoperability between different software tools. Recently such studies are reaching wider recognition and are starting to be included in the academic curricula (SEDLÁČEK et al. 2020).

Our approach integrates photogrammetric data and LiDAR based point clouds with georaster data created with GIS-based analysis and simulation tools. Incorporating multidimensional datasets with a parametric design process requires visualization methods to explore design alternatives in three dimensions and representing time series data generated with simulations. The integration of the parametric design processes with the hybrid dataset was implemented in Rhino and Grasshopper (Rhinoceros 3D 7 SR12). Computational terrain modelling was done with the Docofossor plugin (HURKXKENS & BERNHARD 2019). The generative design process was executed using the Colibri 2.0 Grasshopper plugin (HOWES 2017) published as a part of the TT Toolbox 1.9 (CORE STUDIO 2017). The Design Explorer (HOWES 2016) is directly linked with the Grasshopper Colibri Iterator and was used as a web-based interface to explore the design space. The integration of Grasshopper, SAGA GIS, Docofossor, Colibri, QGIS Section Tools, and DesignExplorer was implemented in Python. The data integration method uses Python libraries commonly used in data science for statistical calculations and interactive graph representations. Furthermore, this study used methods from the fields of geomatics and digital architecture. Geometric parameters needed for the parametric design process were extracted from sections derived from the photogrammetric point cloud data. The method described in PIJL et al. (2020) was used to generate a high-resolution Digital Surface Model that can be used in QGIS (Quantum GIS 3.10). Sections through the photogrammetric Grospoli I model were created with the Profile Tool (Profile Tool 4.8.1), a QGIS plugin, and further processed in Grasshopper and Python.

3 Results

3.1 Deriving Design Parameters from the Large-scale LiDAR Data

The airborne LiDAR dataset related to the territorial scale was used to generate performance metrics that describe existing vineyards. This was done to compare existing terraced vineyards with the generated designs. The results of the analysis are presented in Figure 1. Locations marked as vineyards in the land use data from the municipal GIS database were identified. Systematic identification of terraces in territorial scale has been studied with different approaches (SOFIA et al. 2014, AGNOLETTI 2015, PALIAGA et al. 2020, CUCCHIARO et al. 2021). A detailed elaboration of the systematic terraced vineyard identification would require on-site survey and advanced analysis methods. For the purpose of this study, a slope map was generated from the DTM of the whole valley. For each site marked as a vineyard, the percentage of the area occupied by slopes steeper than 45° was calculated. It was observed that in the terraced vineyards at least 3% of the area is occupied by steep slopes, that is dry-stone walls and embankments. We evaluated the average slope of the landform and manually identified dry-stone walls on the high-resolution orthophoto. In the design phase, this composite slope is differentiated into dry-stone walls, double-curved terrace surfaces and embankments. Figure 5 illustrates the separation of the composite slope into segments. Based on this analysis twelve terraced vineyards were identified. The cadastral outline often did not match the actual boundary of the cultivated areas. In these cases, the plot boundaries were manually corrected based on the orthophoto in the territorial scale. In each of the twelve vineyards, dry-stone walls were traced manually in QGIS. The length of the dry-stone walls the vine rows were traced manually and their total length per m² was recorded. For each terraced vineyard the Potential Incoming Solar Radiation was analysed in SAGA GIS. The median direct solar radiation was calculated for each 15th day in a month in a two-month interval, starting from January. Finally, the terraced vineyard outlines were exported to Rhinoceros and a non-terraced sloped version of the terrain within each outline was generated to calculate the main orientation (mean aspect) and average inclination (mean slope) of each vineyard.

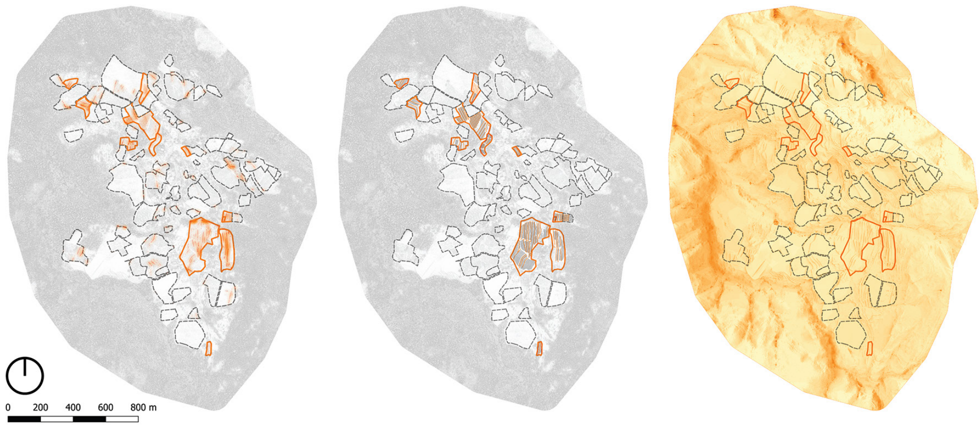

Fig. 1: Terraced vineyard locations were identified using the slope-based method described in 3.1. Dry stone walls and vine rows have been traced to derive quantitative metrics related to vine plants and dry-stone walls (middle). Potential Incoming Solar Radiation analysis was used to measure the solar performance of existing terraced vineyards (right).

3.2 Deriving Design Parameters from the Photogrammetric Point Cloud of Grospoli I Vineyard

Grospoli I is the most complete existing example of a terraced vineyard in Lamole and was therefore selected for further analysis. The vineyard is located on a west facing slope at an altitude of 547-577 meters a.s.l. thereby benefiting from good solar exposure. It consists of six terrace benches, ca. 1220 meters of dry-stone walls, and central water run-off spine (*doccione*) for removing excess rainwater to prevent damage to the terraces and soil. The surfaces of the terrace benches are double curved. Excess rainwater is diverted in two directions. In the cross-sectional direction, excess rainwater is directed towards the upper edge of the dry-stone wall of the next lower terrace. In the longitudinal direction, excess rainwater water is channelled towards the central water run-off spine or towards the edge of the plot. The dry-stone walls benefit from extensive solar exposure until sunset (TYC et al. 2021). The thermal mass of the dry-stone walls modulates ambient temperature, thereby extending the time of the temperature range for photosynthesis. This is of importance in high-altitude locations, where the ambient temperature can drop rapidly after sunset. Hence, orientation, layout and geometry of terraced vineyards are key parameters that determine microclimatic conditions and performance (HENSEL et al. 2018).

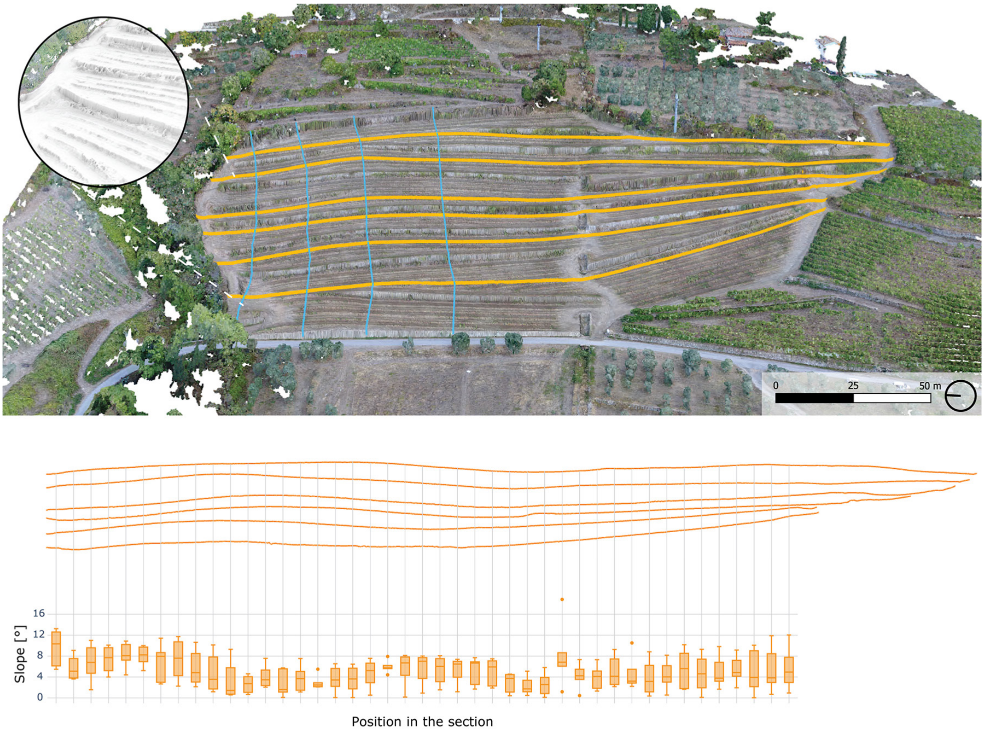

Fig. 2: Longitudinal and cross sections of the Grospoli I vineyard were used to derive geometric parameters. The box plot (bottom) shows slope distribution in the longitudinal section. The circular callout (upper left corner) shows details of earth-riser steps and areas for manoeuvring of the tractor located at the vineyard perimeter.

A high-resolution point cloud of the Grospoli I vineyard was used to derive basic geometric parameters such as heights and slope angles of dry-stone walls and embankments (Table 2). The photogrammetric point cloud was rasterized in CloudCompare (Cloud Compare 2.10.2). Ground points were filtered using the method described by PIJL et al. (2020). Longitudinal sections through the six terrace benches were cut in the space between vine rows and aligned on a shared axis (Fig. 2). Slope values were analysed and lower (10th percentile), median (50th percentile) and upper percentile (90th percentile) were calculated. The direction and value of the slope angle vary along the section. Representative values of slopes were identified by calculating percentile ranges for slope values in the longitudinal sections. An analogous method was applied to analyse four representative cross sections, aligned perpendicular to each dry-stone wall (Fig. 2). In the Grospoli I vineyard terrace benches are divided with additional earth-riser steps (callout in Fig. 3). The soil steps reduce the slope angle of the terrace benches, measured between the edges of the additional terraces located along vine rows. Dry-stone wall and embankment heights as well as slope angles were measured in the cross sections. The results (Table 2) were used as an input for the parametric design process.

Table 2: Geometric parameters and their ranges derived from the analysis of the Grospoli I vineyard dataset

	Lower boundary (10th percentile)	**Median value (50th percentile)**	**Upper boundary (90th percentile)**
Longitudinal slope angle	1°	5°	9°
Cross-sectional slope angle (without earth-riser steps)	8°	8°	10°
Cross-sectional slope angle (with earth-riser steps)	2°	3°	6°
Dry-stone wall height	1.2 m	1.4 m	1.6 m
Dry-stone wall slope angle	77°	79°	79°
Embankment height	3 m	7 m	8 m
Embankment slope angle	30°	45°	45°

3.3 Deriving Design Parameters from Local Tacit Knowledge

The effort to recover land knowledge benefited from interviews with vineyard owners and farmers from Lamole, who are familiar with traditional viticulture based on terraced vineyards and related practices. Interviews were conducted in the period from 2016 to 2021 to obtain information on this type of viticulture, with special focus on the operation of existing terraced vineyards and those that are being reconstructed. In the following we present the insights gained through interviews focused on the Grospoli I vineyard.

Grospoli I was the first reconstructed terraced vineyard of the inner Lamole Valley and consists of two terraced parts located left and right of a central water run-off spine. The former proprietor of the vineyard who undertook its reconstruction clarified that he principally followed the traditional system, yet with some modifications. This included the reconstruction of terraces and dry-stone walls and planting the vine along the height line of the slope. The vine plants were pruned as rows along wires spanning between wood poles. In other reconstructed vineyards the traditional pruning system called *Alberello Lamolese* was implemented with individual plants fixed to wooden poles and trimmed as free-standing plants. In this way *Alberello Lamolese* implies greater solar exposure of each individual plant.

The principal layout of the vineyard adopts the traditional system. However, three modifications were made to facilitate the use of a small tractor for tilling and harvesting: (1) modified inter-row spacing to allow the tractor to move between the rows, (2) implementation of an area for manoeuvring and turning the tractor at the end of the rows, and (3) the introduction of ca. 5-centimetre soil steps every few rows. This solution was observed by the former proprietor of Grospoli I in terraced vineyards in South African vineyards. The soil steps allow for more horizontal surfaces to prevent the small tractors from toppling over. Such tractors have limited lateral stability due to the elevated centre of gravity (GIBSON et al. 1971). Terraced vineyards in Lamole feature a side slope angle of ca. 6-8% in the wall-outward direction for the purpose of rainwater run-off. The height steps implemented in the Grospoli I vineyard minimize the impact of the side slope on the mechanized operation, while ensuring sufficient water run-off. Areas directly adjacent to the dry-stone walls and steep embankments at the vineyard perimeter are not accessed by the agricultural machines in order to minimize operational and structural risks.

3.4 Deriving Design Parameters and Performance Metrics Based on Five Fields of Investigation

Key characteristics of terraced vineyards were identified and related to five fields of investigation based on the interviews and surveys (Fig. 3). Design parameters, constraints and evaluation metrics were listed and from each field of investigation one design input parameter and one design output is selected. These represent quantifiable evaluation metrics or constraints that need to be met. Further analysis was conducted to identify parameters that are relevant for the data-integrated and performance-oriented computational design process.

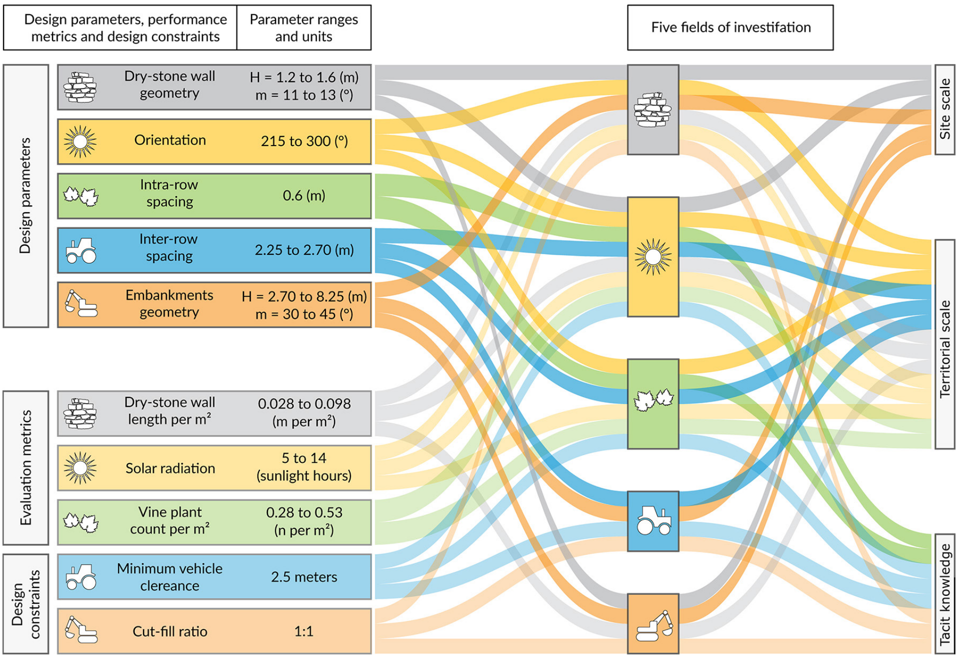

Fig. 3: Five fields of investigation and design parameters, design constraints and evaluation metrics derived from them. Values presented in the figure are derived from the analysis described in previous paragraphs. Numerous intersections suggest that a wider, systemic design approach, incorporating both geometric and non-geometric parameters, should be considered.

For the dry-stone walls parameters include minimum and maximum heights and slope angles derived from the photogrammetric point cloud. The corresponding evaluation metric is the total length of dry-stone walls per m². Wall construction related to the slope angle influences the area occupied by the wall. The input parameter related to vine plants is the intra-row plant spacing derived from on-site measurements. The total vine plant count per m² results from the row lengths. Intra-row plant spacing was evaluated in the process. Regarding solar exposure, the main orientation of the vineyard (median aspect) is used as a design parameter. The Potential Incoming Solar Radiation was simulated for each generated vineyard geometry. The input parameters related to earthworks include embankment heights and slope angles and each design variation was required to reach the balanced cut-fill ratio calculated with Docofossor (HURKXKENS & BERNHARD 2019). The input parameter related to on-site logistics is the minimum clearance for agricultural vehicles, which defines inter-row spacing. Manoeuvring areas for the agricultural vehicles (tractors) along the required sides of the site perimeter were generated in the computational design process. The geometry of the embankments was adapted to create areas with no side slope angles.

The relations between the fields of investigation and variables derived from them are represented by coloured ribbons in a form of a parallel categories diagram (Fig. 3). Relations between the inputs and outputs of the same field of investigation were assigned to the same category and marked with matching colours. Intersections of inputs and outputs related to different fields of investigation are visible in the middle row, where ribbons in different colours are connected to a single category representing a field of investigation. Design inputs in the upper part of Figure 3 are shown as fully opaque ribbons, while design outputs in the lower part are shown in matching colours with reduced saturation. Design parameters, design constraints and evaluation metrics are linked to the scale from which they are derived.

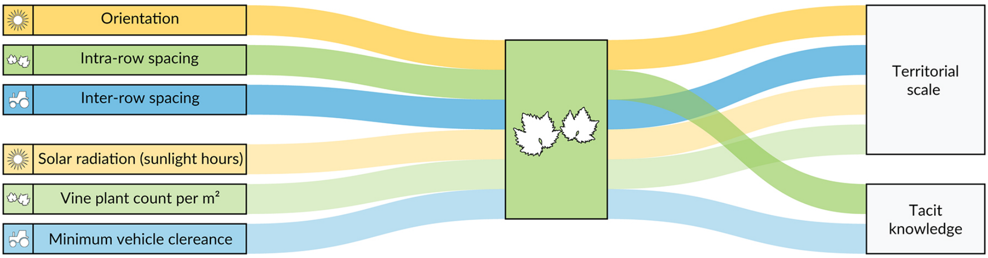

Fig. 4: Field of investigation related to the vine plants and associated design inputs and outputs extracted from Figure 3. Detailed description presented in the following paragraph.

An extract of Fig. 3 related to vine plants is shown in Fig. 4. This field of investigation is influenced by vineyard orientation (vine plant sun exposure) and inter- and intra-row spacing. Ranges of vineyard orientations and inter-row spacing were derived from the aerial LiDAR dataset in the territorial scale. Ranges of insolation were also calculated for all existing vineyards based on data in this scale. Data from interviews was used to approximate vine plant counts per m² based on reported inter-row spacing and total vine row lengths measured in the territorial scale. The terraced vineyards in the Lamole valley are operated by different proprietors with differences in mechanised operation, minimum vehicle clearance and resulting inter-row spacing. Based on the interviews the output parameter related to the minimum vehicle clearance was set to 2.5m.

3.5 Designing with Identified Parameters and Performance Metrics

Mario Carpo stated that generalization and abstraction introduces meaning and choice, while also enabling dialogue (2018). Together designer and stakeholders can choose relevant elements and parameters for the design process with which a series of possible design solutions can be generated. The collection of possible solutions is referred to as design space.

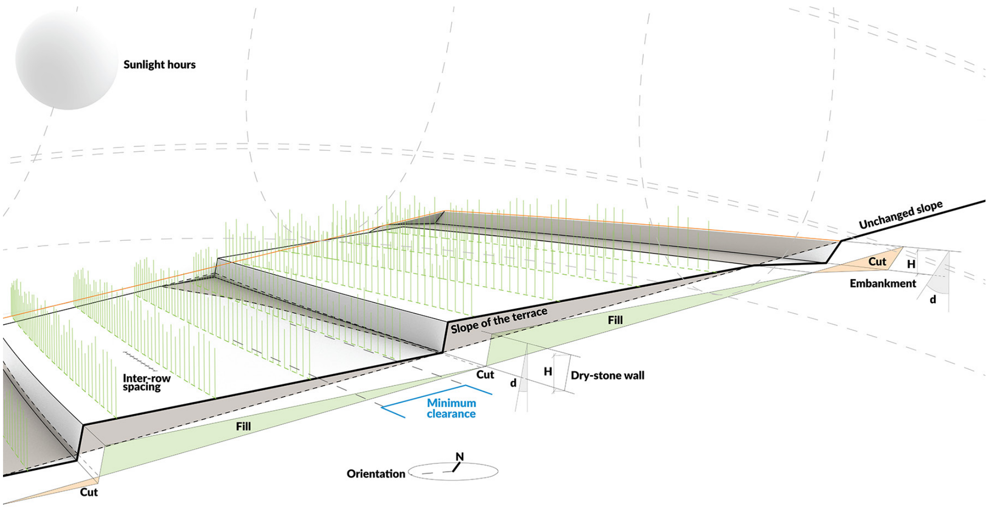

Fig. 5: Diagram showing the design parameters, design constraints and evaluation metrics presented in Fig. 3

Existing approaches to parametric design of terraced landforms (SHAO et al. 2013, BAY et al. 2014, BERČIČ & AŽMAN-MOMIRSKI 2020) are driven by basic geometric parameters, e. g., terrace count or depths. Our approach extends existing ones by introducing additional parameters and performance metrics. Designs are generated on a patch of conical surface limited by rectangular outline, referred to as model site. The dimensions of the site outline, surface inclination and orientation are derived from the minimum and maximum dimensions of the terraced vineyard sites identified in the LiDAR dataset. The generalized model site displays geometric affinity with the studied sites. First embankments are constructed at the site perimeter, thereby generating the height difference for manoeuvring areas at the vineyard perimeter area without side slope inclination. In the existing vineyards the upper edge consists of either earth embankment or dry-stone wall, descending to form the upper edge of the uppermost terrace bench. This was incorporated into the design process, considering the parameter ranges presented in Fig. 3. The construction of the terraces is a series of cut and fill operations, resulting in a balanced cut-fill ratio. In the parametric design process for both the embankment and terrace construction, the cut-fill ratio is calculated with Docofossor (HURKXKENS & BERNHARD 2019). Finally terrace surfaces are moved in the vertical direction to ensure a balanced cut-fill ratio.

The generative design process implemented in the Colibri Iterator is based on a brute force solver (HOWES 2017). The latter is computationally intensive with the generation of the datasets presented in this study requiring several days of computation, resulting in gigabytes of georaster data created with Docofossor and SAGA GIS solar simulation. The aim of the generative process was to generate design variations that are comparable with the existing terraced vineyards. The input parameters included site outline dimensions, main orientation, and inclination. For other input parameters the median value or single value presented in Figure 3 were used as constants. Performance metrics available for both the existing and designed examples were recorded for further evaluation. These included vine plant count per m^2, wall length per m^2 and median daily sunlight hours in six representative days throughout the year. The initial design space contained 1800 design variations but given the computational constraints of brute force-based methods, the number of steps along the parameter ranges was decreased, as suggested by the authors of Colibri Iterator (HOWES 2017). In result 320 design variations were generated. A balanced cut-fill ratio was achieved utilizing a basic self-adaptive mechanism. This non-iterative mechanism resulted in a change of the dry-stone wall heights. The non-iterative character of the parametric design process prevented further automated adjustments of the dry-stone wall heights. The results of the generative process were visually screened, and subsequently filtered and validated in Python. The final generated dataset consisted of 97 design variations that were converted to a file format accepted by DesignExplorer. The parameters derived from twelve existing vineyards were merged with the 97 generated examples. This enabled comparison of real-world examples and generated designs. This additional validation step consists of visual screening of the parameters related to generated and existing vineyards.

3.6 Informing Design decisions Through Design and Performance Space Exploration

The design solutions generated via the parametric process and their matching performance metrics were exported to DesignExplorer, a web-based interface that makes it possible to browse the exported examples based on criteria related to design parameters and performance metrics. In this study this interactive interface was used to explore and validate the generative design process results (Fig. 6).

The interface contains a parallel plot where parameter ranges can be set (Fig. 6 top). The first four columns, labelled with black font colour, are input parameters. The following by columns, labelled with blue font colour, are the performance metrics. The ranges of parameters and performance metrics indicate examples that fulfil specified criteria. For example, narrow vineyards located on moderate slopes that receive at minimum seven sunlight hours per day in a specific month can be selected. Furthermore, terraced vineyard examples that are interactively updated when the parameter ranges are changed can be shown (Fig. 6 bottom). Existing vineyards are shown as colour images with context and designed vineyards are shown as line drawings. Figure 6 shows extracts from the Composite Voxel Model. A voxelised representation is generated for each existing vineyard, where geometric data is augmented with data representing environmental performance. For each terraced vineyard example, a coloured line in the parallel coordinates plot is drawn. This line represents the position of this example in the DesignExplorer multidimensional space. Dimensions are represented as vertical axes in the parallel coordinates plot and refer to geometric parameters and performance metrics. The multidimensional design space resulting from the generative design process and the multidimensional space of the *Composite Voxel Model* can be projected to the dimensions represented as vertical axes in the DesignExplorer parallel coordinates plot. This is made possible by data integration and analysis tools that can be used both with gridded geospatial datasets and terraced vineyard layouts created in the generative design process.

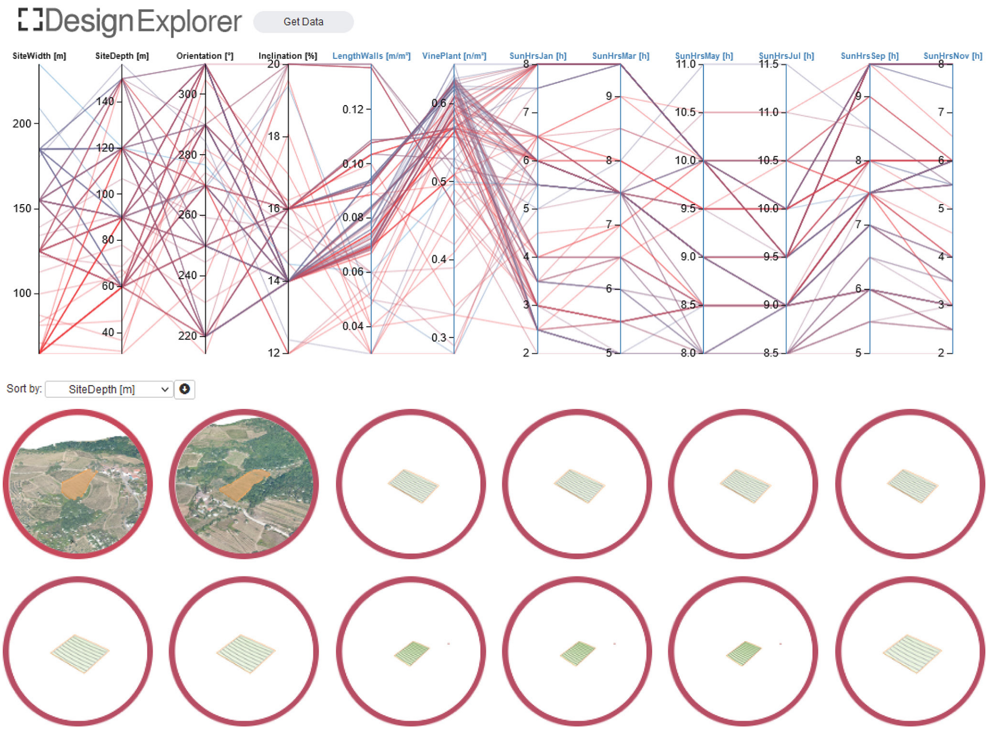

Fig. 6: DesignExplorer interface displaying dataset that describe basic geometric parameters and performance metrics of existing vineyards and designed ones

The DesignExplorer interface can reveal trade-offs between parameters and performance metrics. Relations between vineyard orientation and geometry, and solar exposure in different seasons can be examined. At the same time new insights can be derived such as, for instance, correlations between growing inclination and length of dry-stone walls resulting in a decreasing count of vine plants. However, the existing Grospoli II vineyard shows the opposite trend, thereby indicating the need for further validation of the knowledge derived from the Grospoli I.

4 Discussion

Recently growing interest in traditional viticulture in Lamole and reconstruction of terraced vineyards can be observed. This establishes a context for the likely application of a data-integrated and performance-oriented computational design processes. In the case of the presented workflow the design process was informed by data derived from surveys and different types of simulations. However, the scope of this study is limited by factors such as availability, accuracy, and resolution of relevant data. High resolution data is currently sparse, as only a few terraced vineyards have been photogrammetrically surveyed thus far in Lamole. Improved geospatial analysis methods that enable automatic identification of dry-stone walls and ground point filtering can help to advance this research. The computational design process presented in this paper can be advanced by the introduction of feedback loops to generate a larger number of valid design solutions. However, the introduction of iterative steps will increase computational complexity and the time required to generate design outcomes.

The integration of the territorial and site scales made it possible to identify relevant parameters for the design process. The Grospoli I vineyard was used as a case study with available photogrammetric data. Additional high resolution photogrammetric datasets are required to improve the understanding of constraints related to the local terraced vineyard typology. Methods to effectively derive and validate the geometric parameters from point clouds are required to extend the scope. The GIS-based solar analysis method used in this study depends on 2.5D representation of the terrain. This method is well suited for scales incorporating whole vineyards or the larger territorial scale. However, it is limited in relation to three dimensional objects. The application of architectural solar analysis tools was considered (TYC et al. 2021). The mesh conversion process for high resolution data of objects in this scale limits the application of such tools in this context.

Methods from the field of geomatics for creating DTMs from photogrammetric point clouds in terraced locations (PIJL et al. 2020) and automated terrace identification (SOFIA et al. 2014, AGNOLETTI 2015, CUCCHIARO et al. 2021) can be applied in further studies. Specific methods of automated terraced identification can be combined with the analysis of site outlines for the local mosaic of land use. Sites allocated for vine production are often only partially cultivated and there exist vineyards that consist of terraced and non-terraced parts. Quantifiable parameters can be derived from the territorial scale data only if site outlines are vectorized and validated with orthophotographs or on-site surveys.

In this study Colibri Iterator was used to generate design variations. This method, referred to as brute force optimization, iterates through all possible parameter combinations defining the size and resolution of the design space (HOWES 2017). In brute force algorithms, computational complexity is proportional to the number of candidate solutions contained in the design space, and adding parameters or dimensions significantly increases computational complexity. This problem, known as combinatorial explosion, limits the applicability of brute force solvers in real-word scenarios. In this study the resolution of the design space was therefore limiting the number of designs that could be generated. In this study a probabilistic, non-iterative design process was developed that does not introduce additional complexity into the process. However, brute force optimisation methods have the practical advantage that all candidate solutions are considered, and no optimisation goals are set in advance. Designers can learn about the trade-offs between design parameters through design space exploration with tools such as DesignExplorer.

The presented design process does not include feedback loops and its computational performance was linearly related to the size of the input data (size of the vineyard outline). This limited the overall computational complexity of the generative design process. Validation served to discard a significant number of generated designs. The inclusion of design constraints related to 1:1 cut-fill ratio resulted in a parameter trade-off (dry-stone wall height versus cut-fill ratio) that exceeded the capacity of a non-iterative design process for several generated designs. This problem will be addressed in the future research by introducing a feedback loop mechanism via iterative optimisation algorithms. Optimisation algorithms embedded in the design process can be used to generate valid solutions that fulfil design constraints. At the same time, misalignment between traditional agricultural practices and contemporary understanding of optimization approaches was outlined in the introduction. The role of secondary optimisation algorithms embedded within the primary generative design process is discussed below. The primary generative design algorithm generates multiple design outputs that fulfil defined performance criteria and show resilience under a range of changing conditions. The role of the secondary optimisation algorithm can serve to reduce computational complexity rather than generating a single optimal solution.

In further research steps further trade-offs related to input parameters and performance metrics will be studied using information visualisation methods such as the DesignExplorer. For example, for an existing site, trade-offs between geometric layout and resulting solar exposure, resulting vine plant count and dry-stone wall lengths can be evaluated. Parameter trade-offs related to the secondary, embedded optimisation process can be addressed to some degree with multivariate optimisation processes, such as the HypE algorithm included in the Octopus Grasshopper plugin (VIERLINGER 2013). In the context of solar performance optimization, surrogate model-based methods (WORTMANN 2017) or supervised machine learning (ML) based methods (SEBESTYEN & TYC 2020) will be considered. A multi-step process consisting of generative design stages followed by visual evaluation steps can serve to select relevant parameters, as well as limiting the size of design space for the next generative step independently from the optimisation algorithms utilised by the generative processes. Progressing beyond discipline specific tools to facilitate transdisciplinary collaboration oriented visual interfaces can be key to identifying relevant parameters, parameter trade-offs and defining parameter values that are selected for a particular location.

A key question concerns likely future developments that can be anticipated for the adaptation of traditional agricultural systems to changing conditions, as this will have significant impact on the further development of the research. One likely scenario entails the implementation of data-related technologies, which are already implemented in Smart Agriculture (SA) albeit currently on a more industrial scale. Smart agriculture utilizes Internet of Things (IoT) technologies, networks of smart sensors recoding real-time data (CASTRIGNANÒ et al. 2020). Extending the scope from design to maintenance and operation entails continuous data-collection and monitoring. This can lead to targeted decision support and to information-based adaptive response to climate change and other environmental dynamics. Design solutions, whether implementing new vineyards or adaptation of existing ones, can both be addressed with a performance-oriented generative computational design process. Machine learning algorithms can build on the spatiotemporal correlations in the presented multidimensional dataset. Progressing into three-dimensional representation of vineyard geometry and inclusion of temporal dimension is particularly important in the context of terraced landscapes, where the geometry impacts upon numerous performance requirements. The resulting three-dimensional models can be used for drone path planning in complex, terraced locations, both for surveying and to support vineyard operation. In the field of SA drone based multispectral imaging is frequently used for calculating vegetation indices, e. g., to map plant water stress. New applications of drones in SA, such as crop protection or fruit collection have emerged. Connecting our research related to data-integrated design to SA related technologies is a promising direction for future research. Constraints related to on-site logistics can be adapted to meet the requirements of future autonomous vehicles, both ground-based and aerial. At the same time, requirements of the IoT devices can be incorporated into the integrated design process, for instance to inform sensor type selection and sensor network placement.

However, it is also necessary to consider a broad range of traditional sustainable practices and how these can be integrated into data-driven design and operation of traditional systems like high-altitude viticulture in Lamole. For instance, SA enables targeted implementation of specific actions such as targeted application of industrial fertilizer. In contrast, traditional methods frequently involve biodiversity, i. e., planting other plant species between vine plants that deliver required nutrients to the soil. Hence, sustainability parameters and metrics will need to be added as a way of determining and facilitating adequate operations. Further research will hence focus on continuing documentation of local knowledge through interviews with local farmers.

5 Conclusion and Outlook

This article portrays the current stage of development of a data-integrated and performance-oriented computational design framework for terraced vineyards. The main objective was to initiate the work on this framework by developing a multi-scalar data integration method. Data integration required identification of relevant datasets and analysis methods. This study used design as a method of inquiry for developing a generative design process. The identification of trade-offs related to design parameters and performance metrics benefitted from the use of advanced information visualisation techniques. The availability of high-resolution geospatial data limited the scope in which the steps related to data collection and processing were implemented. To address this limitation further surveys are planned. The data analysis related to the territorial and site scales was limited by the methods applied in this study. This will be addressed in further research through the advancement of analytical methods, including ground point filtering and automated terrace identification methods. The non-iterative generative design process limited the design space considerably. Therefore, the framework will be further developed with the aim to implement an iterative process to overcome limitations related to parameter trade-offs that are currently unsolvable with non-iterative algorithms. Advancing the role of information visualization in the context of interdisciplinary collaborative planning processes will also be a focal area of further research. Furthermore, we will expand the interdisciplinary scope. The inclusion of further knowledge fields and disciplines will serve to include relevant performance related aspects and methods. The role and contribution of experts from different fields in the definition of design parameters and related trade-offs will be addressed on the level of collaborative processes with the aim to develop targeted decision support.

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