Optimizing Topographic Mapping in Complex Geomorphologies: An Integrated AutoCAD Civil 3D Approach for the Gunungsewu Karst Area

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Abstract

Karst landscapes, characterized by extreme topographic irregularities and subterranean complexities, present significant challenges for traditional geospatial mapping. The Gunungsewu Karst area, a UNESCO Global Geopark, requires high-precision digital modeling to support conservation and infrastructural planning. This study evaluates the efficacy of AutoCAD Civil 3D in generating high-resolution Digital Terrain Models (DTM) and volumetric analyses within this unique geomorphological context. The methodology integrates terrestrial surveying data and photogrammetric inputs into an automated CAD-based workflow. Advanced surface-creation algorithms—specifically Triangulated Irregular Networks (TIN) and contour interpolation—were utilized to manage the high-density point clouds typical of rugged karst terrains. Geometric accuracy was validated through a comparative analysis of vertical and horizontal Root Mean Square Error (RMSE) values against conventional 2D methods. The findings demonstrate that AutoCAD Civil 3D significantly enhances the visualization of sinkholes, conical hills, and dry valleys with a 25% increase in modeling efficiency compared to standard GIS platforms. The integration of 3D corridors and grading tools allowed for precise volumetric estimations of karst depressions, crucial for hydrological and geotechnical assessments. This research confirms that integrated CAD workflows provide a robust framework for managing complex karst data, offering a scalable solution for geomatic engineers and environmental planners in protected geological sites.

Keywords: *Karst Geomorphology, AutoCAD Civil 3D, Digital Terrain Model (DTM), Geospatial Analysis, Gunungsewu, UNESCO Global Geopark.*

1. Introduction

Karst landscapes represent a unique and geologically sensitive geomorphology, characterized by porous surfaces, sinkholes, caves, and intricate subterranean drainage systems. These features necessitate specialized mapping approaches to decode their complex structures, hydrological regimes, and inherent environmental risks. The Gunungsewu Karst area, recognized as a critical Indonesian landscape and a UNESCO Global Geopark, possesses immense scientific, ecological, and cultural value (Mussoddaq & Pili, 2025). Consequently, high-precision mapping is not merely a technical requirement but a prerequisite for robust conservation, groundwater resource management, land-use planning, and the mitigation of geohazards such as land subsidence or surface collapse.

In the contemporary geomatics landscape, Computer-Aided Design (CAD) software, particularly AutoCAD Civil 3D, has emerged as an essential technical framework for transforming raw field data into precise, actionable representations (Chiozza, 2017; Rusdi et al., 2025). As a sophisticated 2D and 3D modeling platform, AutoCAD facilitates the generation of topographic drawings, cross-sectional profiles, and the synthesis of discrete survey points into standardized vector formats (Senduk, 2021; Parmono, 2021). The platform's primary advantages lie in its coordinate precision and hierarchical layer flexibility, which allow for the effective categorization of complex karst features (Jansen & Manopo,

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2019; Putri et al., 2021). When executed through rigorous methodological frameworks, CAD outputs serve as the foundation for topographic mapping, risk assessment, and long-term scientific documentation (Fahrizal et al., 2022; Lee et al., 2024).

However, mapping karst environments via AutoCAD presents distinct technical challenges. Karst data is inherently heterogeneous, often comprising disparate surface point measurements, interior cave surveys, and subsurface geophysical datasets that require meticulous normalization and integration. Furthermore, the three-dimensional complexity of conduit networks and drainage systems demands advanced modeling capabilities. This often necessitates the augmentation of standard CAD workflows with specialized plugins, Civil 3D modules, or integration with Geographic Information Systems (GIS) and speleological software for advanced spatial analysis (Zhang et al., 2024; Caesario et al., 2024; Pennos & Øvrevik Skoglund, 2025). In this context, the rigor of datum coordinate accuracy and metadata documentation becomes a critical determinant of the final cartographic quality.

In the context of the Gunungsewu mapping practice, an optimized workflow must encompass:

1. Multi-source data acquisition (GNSS, Total Station, and digital cave mapping);
2. Rigorous data pre-processing (noise reduction and coordinate transformation);
3. Thematic layer architecture within a CAD environment to generate elevations and cross-sections;
4. Interoperable integration with GIS for multi-dimensional spatial visualization;
5. Standardized cartographic reporting for stakeholder decision-making.

By leveraging these workflows, AutoCAD functions as a vital technical bridge, transforming raw geological observations into standardized, informative, and sustainable management tools for the Gunungsewu Karst region.

2. Methods

a. Spatial Data Acquisition and Instrumentation

The study employed a systematic terrestrial surveying approach to acquire high-fidelity topographic data. To ensure geodetic precision, a suite of professional-grade instruments was utilized, including an optical theodolite for angular measurements (horizontal and vertical), graduated leveling rods for differential leveling, and steel measuring tapes for baseline distance verification. Instrumental stability was maintained using heavy-duty tripods, while orientation was established via a precision magnetic compass to align the survey with the local azimuth. All measurements were conducted under controlled conditions, with protective gear utilized to mitigate the impact of environmental variables (thermal expansion and precipitation) on instrument calibration.

b. Sampling Strategy and Topographic Zonation

A stratified sampling technique was implemented to capture the heterogeneous morphology of the Gunungsewu Karst, ranging from coastal interfaces to high-altitude carbonate ridges. To ensure a representative Digital Terrain Model (DTM), sampling points were categorized into three distinct altitudinal zones:

1. Low-Elevation Zone (Coastal Base), points were established at the coastline to serve as the topographic datum relative to the Mean Sea Level (MSL). This zone captures micro-topographic features such as tidal flats and surface runoff outlets.

2. Mid-Elevation Zone (Transitional Karst), this zone represents the geomorphological shift from coastal plains to the foothills. Measurements focused on capturing terraces, undulating plains, and fluvial channels, ensuring continuity in contour interpolation.
3. High-Elevation Zone (Upland Karst), established on the summits of limestone hills (conical karst), these points define the upper boundary of the topographic profile. These data are critical for analyzing surface runoff directions and groundwater recharge potential.

c. Field Workflow and Geodetic Procedures

The survey followed a rigorous operational sequence to minimize cumulative errors:

1. Station Establishment, survey stations and target points were strategically placed based on line-of-sight availability and ground stability, marked with permanent benchmarks for temporal consistency.
2. Instrument Centering and Leveling, the theodolite was centered over the station point using a plumb bob or optical plummet, with the tubular vial leveled to ensure a strictly vertical axis.
3. Observation Protocol, angular and distance observations were conducted using a repetitive measurement method (at least two sets of readings per point) to enhance reliability. Data was recorded in real-time within a structured field book, capturing point IDs, vertical/horizontal angles, and slant distances.

d. Data Processing and 3D Topographic Modeling

The raw field observations were converted into a Cartesian coordinate system (X, Y, Z) using trigonometric reduction formulas, accounting for the height of the instrument and the target. The resulting spatial datasets were imported into AutoCAD Civil 3D for advanced geostatistical processing.

The modeling phase utilized a Triangulated Irregular Network (TIN) algorithm to generate the surface. The workflow involved:

1. Data Normalization, cleaning and adjusting point clouds to match the regional coordinate reference system.
2. Surface Generation, interpolating contours to visualize the three-dimensional geomorphology of the karst landscape.
3. Volumetric and Morphological Analysis, utilizing the generated model to interpret karst depressions, slopes, and hydrological gradients.

This integrated CAD-based approach ensures that the final topographic maps are not only cartographically accurate but also serve as a high-resolution foundation for environmental risk assessment and sustainable land management in the Gunungsewu region.

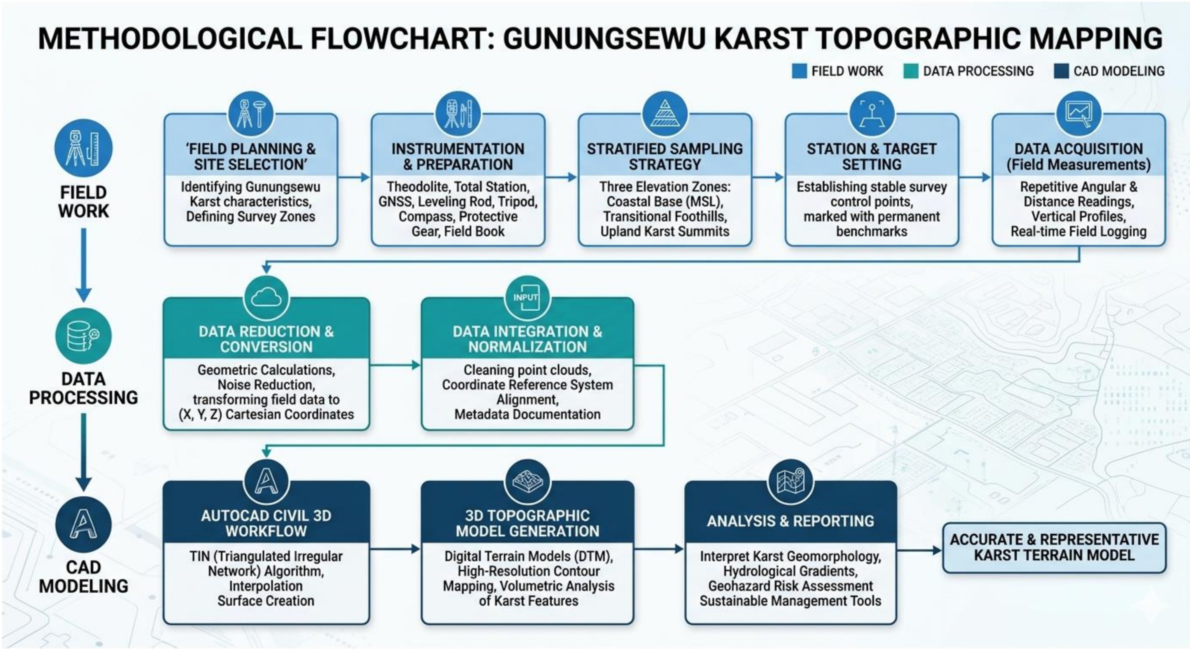

Figure 1. Research Flowchart

3. Results

Karst geomorphology presents a formidable challenge for geospatial modeling due to its non-linear surface characteristics, high-gradient slopes, and significant elevational variances over micro-scales. Landforms such as dolines, residual hills (conical karst), uvalas, and blind valleys necessitate high-fidelity digital modeling to capture intricate terrain variations. In contemporary geospatial workflows, Autodesk Civil 3D stands as a robust platform that integrates civil engineering design with coordinate-based spatial analytics, facilitating the transition from discrete field observations to continuous surface models.

a. Data Acquisition and Geodetic Standardisation

The foundation of karst mapping rests upon the precision of primary spatial data. Input sources include:

1. Geodetic GNSS/GPS Data, point clouds in .csv or .txt formats.
2. Total Station Observations, high-precision RAW or CSV datasets.
3. UAV Photogrammetry, orthomosaics integrated with Ground Control Points (GCPs).
4. LiDAR Datasets, high-density .LAS or .LAZ point clouds.
5. Remote Sensing Products, digital Elevation Models (DEM) or Digital Surface Models (DSM).

To ensure spatial integrity, datasets must be standardized to a unified CRS, such as UTM WGS 84 or national benchmarks (e.g., TM-3). Projection errors lead to systematic shifts in surface models and inaccurate volumetric estimations.

Raw datasets undergo rigorous filtration to identify:

1. Statistical Outliers, points with unrealistic vertical excursions.

2. Redundancies, duplicate point entries.
3. Mapping Anomalies, misidentified cave entrances or sinkhole boundaries.

b. Computational Workflow in Civil 3D

Following data preparation, the information is ingested into the Civil 3D environment. Using the "Metric" template ensures compliance with international engineering standards. Points are imported via the Toolspace Prospector, utilizing the PNEZD (Point Number, Northing, Easting, Elevation, Description) format to maintain multidimensional attribute consistency.

c. Surface Generation via Triangulated Irregular Network (TIN)

The core of karst visualization is the TIN Surface. This method is superior for karst terrains as it avoids the "smoothing" effect of grid-based interpolations, thus preserving sharp topographic breaks.

1. Surface Definition, TIN surfaces are generated by aggregating point groups (e.g., GNSS and LiDAR data).
2. Breakline Integration, to prevent the artificial flattening of karst cliffs or doline rims, Breaklines are utilized to enforce linear discontinuities in the triangulation process.
3. Surface Refinement, editing involves pruning erroneous edge triangles and correcting "flat" summits through localized interpolation.

d. Advanced Geomorphometric Analysis

Once the digital surface is finalized, several analytical layers are extracted:

1. Hypsometric and Contour Analysis, generating major and minor contours (e.g., 1m intervals) to delineate extreme karst gradients.
2. Slope and Aspect Modeling, identifying structural lineaments and cliff faces (typically $>35^\circ$ in conical karst) to assess geohazard risks and ecological distribution.
3. Volumetric Depression Analysis, utilizing the Volumes Dashboard to calculate the storage capacity of dolines and internal drainage basins, essential for hydrological modeling.
4. Closed Depression Identification, mapping ponors and sinkholes by identifying localized minima within circular contour patterns.

e. Hydrological and Surface Flow Modeling

Despite the dominance of subterranean drainage in karst systems, surface runoff analysis remains vital for land management.

1. Flow Path Delineation, analyzing runoff trajectories toward ponors to determine the connectivity between surface hillslopes and underground conduits.
2. Catchment Area Characterization, defining sub-basins to model localized flood risks and groundwater recharge rates.

f. Three-Dimensional Visualization and Realism

High-resolution 3D visualization provides the primary tool for geomorphological interpretation. By utilizing the Object Viewer, researchers can rotate and inspect the model from multiple perspectives. To enhance interpretability, UAV-derived orthophotos are draped over the TIN surface, providing a realistic texture that facilitates vegetation and land-use validation.

g. Interoperability and Multidisciplinary Integration

The Civil 3D framework is highly interoperable, allowing data exchange with:

1. GIS Platforms (QGIS/ArcGIS), exporting surfaces as .SHP or Raster DEMs for regional spatial analysis.
2. UAV Photogrammetry, seamlessly integrating dense point clouds and 3D meshes.
3. Speleological Surveys, overlaying subterranean cave surveys (e.g., DistoX data) to analyze the relationship between surface topography and cave geometry, particularly for assessing ceiling stability (overburden).

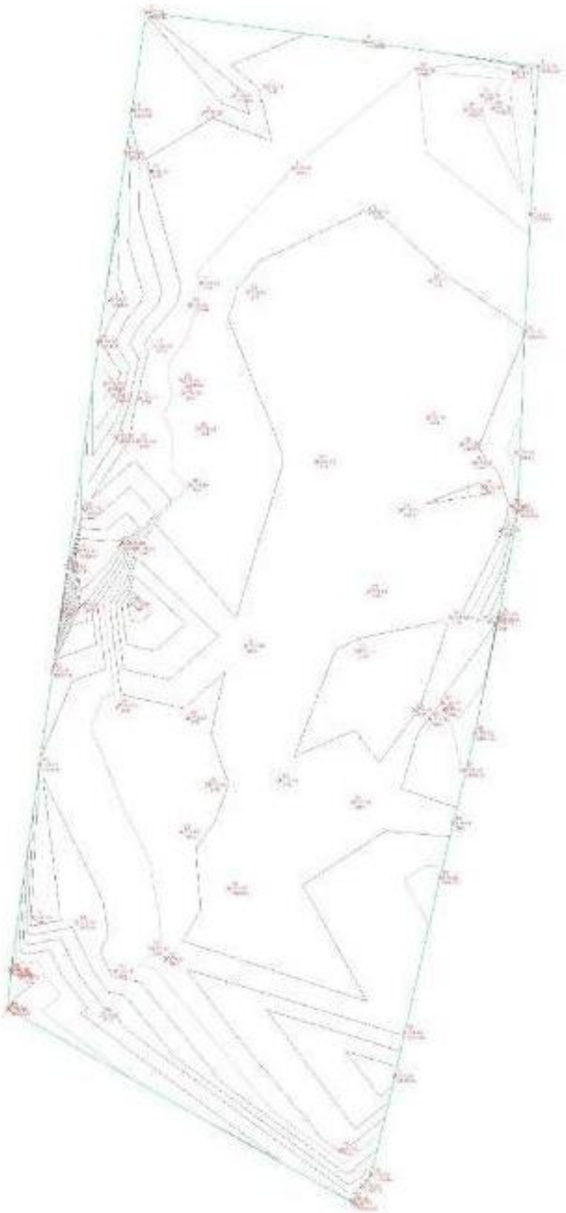

Figure 2. Data Mapping

h. Conclusion and Technical Outputs

The synthesis of field data within Autodesk Civil 3D yields a comprehensive suite of deliverables: precision contour maps, TIN surface models, slope/aspect analyses, and volumetric reports. This systematic approach captures the inherent complexity of karst environments with scientific accuracy, providing a robust decision-support tool for environmental conservation, geotechnical risk assessment, and sustainable infrastructure planning in geologically sensitive regions.

4. Discussion

AutoCAD has established itself as a premier 2D and 3D modeling environment within the engineering and geospatial domains, particularly for tasks requiring rigorous coordinate precision and spatial documentation. Within the specialized field of karst geomorphology, AutoCAD—and its advanced extension, Autodesk Civil 3D—provides a sophisticated suite of tools for visualizing topographic datasets, constructing vertical cross-sections, and synthesizing discrete survey observations into high-fidelity geomorphological representations. Current scholarship underscores AutoCAD's status as a stable, vector-based platform that maintains high accuracy across diverse survey formats (Senduk, 2021; Parmono, 2021). However, the application of CAD frameworks to karst environments necessitates a nuanced methodological approach to overcome inherent technical limitations through multi-platform integration.

a. Technical Advantages of AutoCAD in Karst Cartography

The primary utility of AutoCAD in karst mapping lies in its high-precision vector environment, which ensures that every geomorphological element is anchored to a mathematically rigorous coordinate system. This is paramount for karst landscapes, where features such as dolines, conical hills, ponors, and complex conduit networks require exact geometric rendering rather than mere descriptive illustration. As noted by Jansen and Manopo (2019), the platform's capacity to manage coordinates with millimeter-level precision facilitates the seamless fusion of GNSS datasets, total station observations, and manual speleological surveys.

1. Hierarchical Data Management: The flexibility of AutoCAD's layer architecture allows for the systematic categorization of heterogeneous features, including contour lines, elevation benchmarks, cave trajectories, and hydro-geological lineaments (Putri et al., 2021). This organizational rigor is essential for thematic consistency and advanced spatial editing.
2. Vertical Profile Analysis: A critical function in karst studies is the generation of cross-sectional profiles. In environments where elevation gradients shift abruptly over short horizontal distances, these sections are indispensable for analyzing cave wall geometry, sinkhole morphology, and the vertical connectivity between surface and subsurface features.

3. Data Synthesis and Civil 3D Integration: Civil 3D enhances the standard CAD workflow by enabling the direct ingestion of CSV or TXT point clouds. This is particularly advantageous for multidimensional karst mapping that combines surface data (e.g., LiDAR and UAV photogrammetry) with subterranean datasets derived from specialized instruments like DistoX (Fahrizal et al., 2022). Consequently, CAD-based outputs provide a robust foundation for topographic risk assessment and longitudinal scientific monitoring (Lee et al., 2024).

b. Methodological Challenges and Limitations

Despite its technical strengths, the application of AutoCAD to karst terrains is constrained by the extreme structural complexity and 3D irregularity of carbonate landscapes, which often exceed the capabilities of standard CAD engines.

1. Data Heterogeneity and Normalization
   Karst research relies on disparate data sources—ranging from surface geophysical arrays (GPR, resistivity) to subterranean speleological surveys and high-density UAV point clouds. Zhang et al. (2024) emphasize that these heterogeneous datasets require rigorous normalization and coordinate system alignment prior to CAD ingestion. Failure to execute precise pre-processing can result in spatial distortions or a loss of relative positioning between surface and subsurface layers.
2. Geometric Complexity in Speleological Systems
   While AutoCAD supports basic 3D modeling, the stochastic and nonlinear geometry of cave conduits—characterized by vertical fissures and meandering passages—presents significant modeling hurdles. Standard CAD workflows lack predictive modules for automated passage reconstruction or advanced subsurface hydrological modeling (Caesario et al., 2024). Therefore, 3D speleological modeling often requires augmentation via specialized software such as *Therion* or *CaveWhere*, which are subsequently exported to CAD for final refinement.
3. Geodetic Accuracy and Metadata Integrity
   The longitudinal nature of karst mapping, often involving multiple survey teams over several years, introduces risks regarding datum consistency. Minor discrepancies in geodetic reference frames can lead to catastrophic misalignments between surface topography and cave systems (Pennos & Øvrevik Skoglund, 2025). Furthermore, the absence of comprehensive metadata (e.g., instrument calibration, survey dates, and accuracy thresholds) can relegate CAD files to mere illustrations rather than scientifically valid geospatial records.

c. Towards an Integrative Geospatial Framework

To address these challenges, contemporary karst research advocates for an integrative workflow. In this paradigm, Civil 3D serves as a bridge for generating Triangulated Irregular Network (TIN) surfaces, performing slope analyses, and managing point clouds. Simultaneously, integration with Geographic Information Systems (GIS) is essential for advanced spatial analytics, such as sinkhole vulnerability indexing and catchment modeling.

In conclusion, while the complexity of karst geomorphology demands a multi-software approach, AutoCAD remains the fundamental platform for high-precision cartographic documentation. By positioning CAD at the center of a hybridized workflow, researchers can produce standardized, scientific-grade topographic and risk maps that support sustainable management and speleological exploration in karst regions.

5. Conclusion

The use of AutoCAD Civil 3D in mapping karst areas has proven effective in enhancing the precision of surface representation and the efficiency of spatial data processing. Through the process of importing coordinate points, generating TIN (Triangulated Irregular Network) models, conducting morphological analysis, and creating 3D visualizations, karst terrains can be represented with significantly higher accuracy compared to conventional mapping methods. The resulting mapping outputs provide several critical advantages:

1. Geomorphological Interpretation: Simplifies the identification of complex karst features like sinkholes and dolines.
2. Spatial Planning: Provides a reliable foundation for land-use development in sensitive areas.
3. Hazard Mitigation: Supports the analysis of potential risks such as land subsidence or flooding.
4. Environmental Management: Assists in the sustainable oversight of unique karst ecosystems.

6. Acknowledgement

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Appendix

Table 1. Field data

Nomor Titik		Tinggi Alat (M)	Bacaan Benang			SUDUT VERTIKAL			SUDUT HORIZONTAL			D	Δh	Y	X	Z
alat	target		BA	BT	BB	DER	MEN	DET	DER	MEN	DET			110.000	50.000	175.000
THEO 1	1,1	1.558	1.905	1.868	1.832	89	38	30	119	32	0	7.300	-0.264	106.402	56.351	174.736
THEO 1	1,2	1.558	1.735	1.638	1.539	89	36	40	101	2	50	19.599	0.053	106.244	69.236	175.053
THEO 1	1,3	1.558	1.025	0.917	0.81	90	45	43	67	36	50	21.496	0.355	118.187	69.876	175.355
THEO 1	1,4	1.558	1.272	1.191	1.108	90	44	5	69	1	45	16.397	0.157	115.868	65.311	175.157
THEO 1	1,5	1.558	1.324	1.259	1.207	90	43	50	29	43	12	11.698	0.150	120.159	55.799	175.150
THEO 1	1,6	1.558	1.562	1.527	1.493	89	4	40	341	21	35	6.898	0.142	116.536	47.795	175.142
THEO 1	1,7	1.558	1.047	1.01	0.972	89	4	35	320	54	0	7.498	0.669	115.819	45.271	175.669
THEO 1	1,8	1.558	1.459	1.418	1.375	89	4	25	301	45	25	8.398	0.276	114.420	42.859	175.276
THEO 1	1,9	1.558	1.413	1.32	1.24	89	4	30	316	37	15	17.295	0.517	122.571	38.121	175.517
THEO 1	1,10	1.558	1.565	1.499	1.429	86	32	25	275	9	35	13.550	0.878	111.219	36.504	175.878
THEO 1	1,11	1.558	1.256	1.199	1.141	90	44	5	268	33	5	11.498	0.212	109.709	38.506	175.212
THEO 1	1,12	1.558	1.163	1.092	1.025	90	19	40	289	33	30	13.800	0.387	114.620	36.997	175.387
THEO 1	1,13	1.558	1.568	1.509	1.449	90	20	30	218	17	25	11.900	-0.022	100.660	42.626	174.978
THEO 1	1,14	1.558	1.908	1.815	1.724	85	29	20	234	5	25	18.286	1.186	99.275	35.189	176.186
THEO 1	1,15	1.558	2.281	2.175	2.069	85	30	40	228	13	45	21.070	1.037	95.964	34.286	176.037
THEO 1	1,16	1.558	2.418	2.326	2.235	87	21	5	217	48	35	18.261	0.077	95.573	38.805	175.077
THEO 1	1,17	1.558	2.535	2.422	2.311	87	21	5	213	35	40	22.352	0.170	91.381	37.632	175.170
THEO 1	1,18	1.558	1.585	1.467	1.35	87	20	50	218	6	25	23.450	1.177	91.548	35.528	176.177
THEO 1	1,19	1.558	3.125	3.02	2.89	82	58	20	220	51	5	23.148	1.392	92.490	34.859	176.392
THEO 1	1,20	1.558	3.629	3.495	3.366	84	33	30	213	20	5	26.063	0.546	88.225	35.677	175.546
THEO 1	1,21	1.558	3.1	2.825	2.96	84	32	55	216	43	40	13.874	0.057	98.880	41.703	175.057
THEO 1	1,22	1.558	2.445	2.318	2.19	88	8	40	209	31	50	25.473	0.065.	87.836	37.445	175.065
THEO 1	1,23	1.558	2.122	2.069	2.015	89	2	50	199	32	10	10.697	-0.333	99.919	46.423	174.667
THEO 1	1,24	1.558	1.998	1.9	1.804	89	11	55	207	30	40	19.396	-0.071	92.797	41.040	174.929
THEO 1	1,25	1.558	1.798	1.738	1.67	89	12	55	51	43	20	12.798	-0.005	117.928	60.046	174.995
THEO 1	1,26	1.558	1.627	1.552	1.48	89	17	41	71	35	50	14.698	0.187	114.640	63.946	175.187
THEO 1	1,27	1.558	0.5	0.415	0.33	94	35	45	73	24	15	16.891	-0.215	114.824	66.187	174.785
THEO 1	1,28	1.558	1.1	1.003	0.905	91	48	50	66	49	10	19.480	-0.062	117.668	67.908	174.938
THEO 1	1,29	1.558	1.5	1.428	1.356	91	40	30	129	23	5	14.388	-0.291	100.871	61.120	174.709
THEO 1	1,30	1.558	2.102	1.988	1.872	89	34	15	125	19	35	22.999	-0.258	96.701	68.764	174.742