Satellite Data for Economic Insights: Towards Tracking Automotive Production in Germany With Sentinel-1 for Economic Nowcasting

Franziska Kraft, Sandro Martinis, Christian Krullikowski, Simon Plank, Anca Anghelea, José Manuel Delgado Blasco, Klara Schönenberger, Maren Köhlmann, and Melanie Brauchler

***Abstract*—The increasingly dynamic nature of the global economy has heightened demand for real-time economic data, particularly during crises when traditional macroeconomic indicators have struggled to capture the extent of economic impacts. Innovative methods based on satellite remote sensing data have the potential to close this gap. This study investigates the potential of developing a novel economic indicator using Sentinel-1 synthetic aperture radar data to estimate production levels in the German automotive industry. Production parking lot occupancy is tracked at 18 domestic production sites to approximate production levels, leveraging openly available, semi-daily, high-resolution, and weather-independent satellite imagery for continuous monitoring. The analysis demonstrates a strong correlation of 0.74 between production parking lot occupancy and publicly available production figures, highlighting the method's potential for near real-time economic insights. However, challenges remain in inferring production levels from production parking lot occupancy alone, especially in accurately capturing temporary production disruptions due to data limitations and site-specific variability. While the approach shows promise for complementing traditional economic measures, future research should refine the methodology and explore applications in other sectors, such as retail and tourism. Overall, this study underscores the potential of openly available remote sensing data for economic nowcasting, providing timely insights to support industry stakeholders and policymakers in data-driven decision-making in uncertain economic environments.**

***Index Terms*—Automotive production, economic nowcasting, real-time economic monitoring, Sentinel-1.**

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I. Introduction

DEMAND for up-to-date data on the state of the economy has risen sharply due to the increasingly dynamic nature of the global economy. In an era of compounding uncertainties, timely decision making by policymakers and other stakeholders has become paramount. Economic uncertainty is especially high during times of crisis, where traditional economic indicators have struggled to keep pace with the velocity of modern crises. For example, the outbreak of the COVID-19 pandemic required the immediate implementation of countermeasures to contain it, which impacted the global economy immensely almost overnight [1], [2], [3]. Germany's gross domestic product (GDP), for example, fell by almost 10% in the second quarter of 2020 [4]. However, it was difficult to gauge the exact extent of the economic impacts while they were unfolding due to the unprecedented speed and nature of the shock. In such volatile situations, real time data becomes essential for policymakers to monitor economic trends as they unfold, allowing for the timely design and implementation of targeted interventions as well as for a continuous evaluation of policy effectiveness. Yet, traditional short-term macroeconomic indicators commonly depend on models, which are based on historical relationships between certain inputs and cannot capture changes in these patterns in times of severe crisis. Compounding this issue is the delay in publishing economic indicators, which can sometimes be substantial [1], [2], [3]. For instance, crucial data on industrial output from March 2020, when the first lockdown of the COVID-19 pandemic significantly impacted Germany's economy, was not released until early May 2020 [1]. Key aggregated indicators like the GDP are usually available only after the end of each quarter [5], are prone to revision, and can therefore only provide a backward-looking evaluation of impacts [6], [7]. In Germany, initial GDP results are currently published around 30 days after the end of each quarter, with efforts underway to shorten this period to 10 days. However, earlier provision of results requires additional estimates, which could also be supported by real time economic indicators [5], [8].

Innovative data sources and methodologies are needed to address this need for timely economic insights to complement traditional economic measures. Satellite remote sensing provides a promising tool for real-time economic monitoring, offering systemic observations of the Earth, unconstrained by administrative borders, reporting delays, or revisions.

However, the use of satellite data for economic monitoring also presents challenges. For one, the interpretation of satellite imagery requires sophisticated algorithms to extract meaningful economic signals from the data as the relationship between physical changes observed from space and economic activities on the ground is complex and may vary across different contexts and sectors. Furthermore, the temporal and spatial resolution of openly available remote sensing data could limit the development of robust indicators. Despite these challenges, studies have demonstrated the potential of satellite data for economic monitoring. The majority of studies exploit night light data to assess economic activity overall (e.g., [9], [10], [11]). Others have used optical imagery to derive the number of cars parked in retailer parking lots to assess their financial performance [12]. However, estimating industrial activities with remote sensing data is less straightforward and less studied. d'Aspremont et al. [13], for example, developed an economic indicator, which monitors cement production based on satellite infrared data.

The present study aims to investigate the potential of developing a novel economic indicator estimating production levels of the German automotive industry based on a prototype implemented as part of the Rapid Action for COVID-19 and Earth Observation initiative of the European Space Agency and the European Commission Directorate-General for Defence Industry and Space [14], [15]. The automotive industry is a critical sector of the German economy, accounting for almost 4% of the country's GDP in 2021 [16], and its activity levels can provide insightful proxies for the overall state of the economy. Using openly available high-resolution Sentinel-1 synthetic aperture radar (SAR) satellite data, the new indicator monitors occupancy levels of production parking lots at domestic automotive production sites. These serve as a real-time proxy for production levels, based on the assumption that an increase in newly produced vehicles will also lead to a rise in vehicles parked in these production parking lots.

II. Methods

A. Selection of Automotive Production Facilities

Germany is home to a globally significant automotive industry, with 24 major vehicle production sites operated by eight manufacturers. These facilities vary in size, production capacity, and specialization, producing a wide range of vehicle models for both domestic and international markets. To assess the feasibility of using Sentinel-1 data for monitoring production activity, a selection process was conducted to identify suitable production sites based on specific criteria. As a first step, the suitability of domestic vehicle production sites was examined by verifying the following conditions through very high-resolution optical satellite imagery across multiple time periods:

1) the facility includes open-air parking lots designated for produced vehicles;
2) these parking lots remain unobstructed by other structures;
3) they are clearly used for vehicle storage rather than other purposes, including employee parking;
4) their layout remains stable throughout the observation period.

Based on these criteria, a total of 18 suitable and 6 unsuitable production sites were identified (see Fig. 1, Tables I and II). For the 18 selected sites, all production parking lots that met the conditions outlined above were digitized manually using the QGIS software.

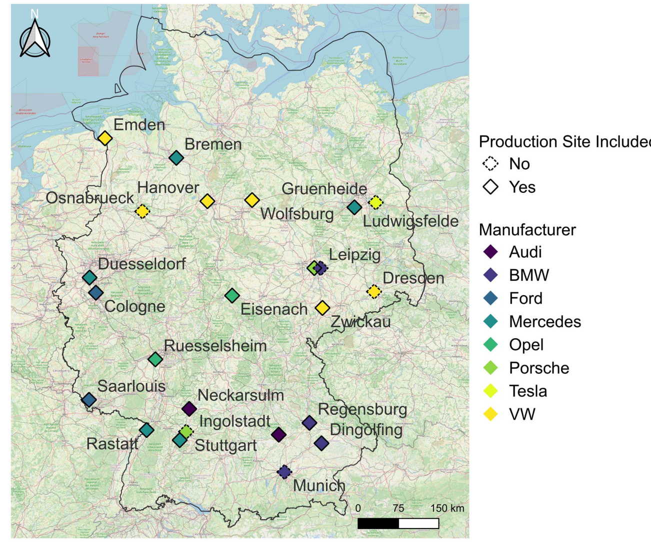

Fig. 1. Overview of domestic automotive production sites by manufacturer in Germany. Production facilities included in the study are marked with a solid outline, excluded production facilities with a dotted outline. Basemap: © OpenStreetMap contributors (https://www.openstreetmap.org/copyright), distributed under the Open Database License (ODbL).

TABLE I
Automotive Production Sites in Germany Selected for Sentinel-1-based Production Monitoring

Manufacturer	Number of Sites	Vehicle Type	Location(s)	Annual Production (2023)
Audi	2	Cars	Ingolstadt	~ 404 000
			Neckarsulm	–151 000
BMW	2	Cars	Dingolfing	~ 292 000
			Regensburg	~ 238 000
Ford	2	Cars	Cologne	~ 88 000
			Saarlouis	~ 138 000
Mercedes	3	Cars	Bremen	–277 000
			Sindelfingen	~ 222 000
			Rastatt	~ 206 000
	2	Trucks	Duesseldorf	~ 131 000
			Ludwigsfelde	~ 56 000
Opel	2	Cars	Eisenach	~ 54 000
			Ruesselsheim	~ 107 000
Porsche	1	Cars	Leipzig	~ 121 000
VW	3	Cars	Emden	~ 180 000
			Wolfsburg	~ 490 000
			Zwickau	~ 247 000
	1	Trucks	Hanover	~ 154 000
Total	**18**			

TABLE II
Domestic Automotive Production Sites Unsuitable for Sentinel-1-based Production Monitoring

Manufacturer	Location(s)	Reason for Exclusion	Annual Production (2023)
BMW	Munich	Indoor storage	~ 218 000
	Leipzig	Production parking lot instability	~ 188 000
Porsche	Stuttgart	Sheltered storage	~ 108 000
Tesla	Gruenheide	Insufficient time series	~ 193 000
VW	Osnabrueck	Indoor storage	~ 18 000
	Dresden	Indoor storage	~ 6000

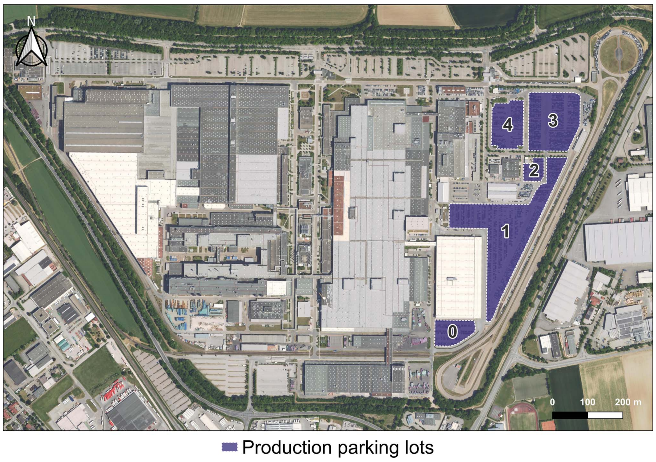

Fig. 2. Individual production parking lots at the BMW production site in Regensburg. Basemap: Bayerische Vermessungsverwaltung – www.geodaten.bayern.de, distributed under CC BY 4.0.

The outlines of the relevant production parking lots were traced using the latest very high-resolution optical imagery, leaving out any obstacles, including vegetation, that could potentially interfere with or distort the backscatter signal. Where openly available, site plans were consulted. Each production parking lot was assigned a unique ID (see Fig. 2) to allow for them to be analyzed separately.

B. Sentinel-1 Data

This study utilized Copernicus Sentinel-1 data [17], [18], a freely available source of radar satellite imagery collected by a C-band SAR sensor. Unlike optical sensors, Sentinel-1 radar data are not affected by atmospheric conditions such as cloud cover. Additionally, the active radar system enables both day and night imaging. These advantages allow for continuous and systematic monitoring of the Earth's surface, making the data suitable for the development of the indicator. Until December 2021, two satellites, Sentinel-1A and Sentinel-1B, were in orbit 180° apart, allowing for a revisit period of six days. While it increased to twelve days after the loss of Sentinel-1B in December 2021, overlapping orbits can lead to shorter revisit times. For the selected sites, revisit times therefore ranged between one and twelve days. In December 2024, the Copernicus Sentinel-1C satellite was successfully launched, promising a return to the nominal observation scenario with shorter revisit times in constellation with Sentinel-1A.

Sentinel-1 provides data in various polarizations and modes from 2014 to the present. In this study, geolocated Sentinel-1 ground range detected (GRD) Level-1 data acquired in interferometric wide swath mode (IW) was utilized, which has a spatial resolution of 20×20 m [19]. The analysis used GRD-IW data in VH polarization, which was shown to be more sensitive to the presence of vehicles than data in VV polarization during the development of the indicator.

The backscatter signal recorded by radar sensors, such as Sentinel-1, is sensitive to surface roughness and the dielectric properties and structure of the recorded objects on the ground. Flat objects in the order of the C-band wavelength (~5.55 cm) such as calm water surfaces, soil, or roads cause low backscatter as most of the radar signal is reflected away from the sensor. In contrast, vertical features such as trees, buildings, or also cars produce high backscatter due to the so-called double bounce effect, which occurs when the radar signal is reflected from the object to the ground and then from the ground back to the sensor (or vice versa), resulting in a strong return signal. In this way, the presence of cars in parking lots can be detected, with a higher radar signal return indicating a higher number of parked cars and vice versa. Since the outer shell of cars is essentially made of metal (high dielectric constant), the backscattering effect increases significantly compared to the asphalt of the parking lot. Thus, despite its coarse spatial resolution compared to the size of cars, the Sentinel-1 SAR system is also sensitive to changes in the parking lot occupancy on subpixel level.

C. Data Preprocessing and Analysis

Data for the selected production sites was requested through the SentinelHub. Through this service users can access Sentinel-1 GRD products with several standard preprocessing steps, such as calibration and geolocation. In addition, the Lee speckle filter with a window size of 3×3 was applied. Due to the flat nature of the production parking lots, no terrain pre-processing was required. The digital pixel numbers were transformed from linear to logarithmic scale

$$\sigma^0 \text{ backscatter}\,[\text{dB}] : 10 \cdot \log\left(S1_{\text{linear backscatter}}\right) \tag{1}$$

The Python package sentinelhub provides direct access to statistical parameters of available Sentinel-1 data via a Statistical API without needing to locally download the actual satellite imagery. In this way, the mean sigma naught (σ^0) backscatter for the individual production parking lots was obtained for all available acquisition times within the overall observation period from October 2014 until June 2024. For each production parking lot, the time series data was analyzed for anomalies to verify selection criterion 4 (stable parking lot layouts), given that very high-resolution optical imagery was only available for limited dates throughout the time period. A final selection of valid parking spaces was then made to calculate the indicator.

To obtain the relative parking lot occupancy at each acquisition date, the data for each selected production parking lot were individually normalized using a min–max normalization approach to account for parking lot-specific characteristics, such as surface material or surroundings, and consequent variations in backscatter response. The min–max normalization was chosen based on the assumption that each production parking lot was completely empty and full at least once during the entire observation period, which could be confirmed from optical imagery for most of the sites. As an influence of the acquisition orbit on the backscatter intensity was found during the development of the indicator, the time series were first split by orbit, normalized separately to eliminate this effect, and then joined again. In many cases, the mean σ^0 backscatter from the ascending and descending orbit for individual production parking lots showed similar trends overall, but within different value ranges, i.e., the

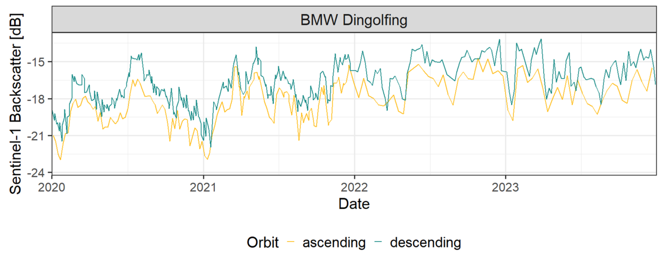

Fig. 3. Mean Sentinel-1 σ^0 backscatter from different acquisition orbits for an exemplary production parking lot at BMW's Dingolfing production site.

backscatter from one orbit was continuously higher than from the other (see Fig. 3). Neither of the orbits showed consistently higher values than the other.

The normalized occupancy data from all valid production parking lots of the same site were then combined using a weighted average based on the size of each production parking lot, as larger lots contribute more to overall vehicle storage. The average occupancy was assumed to represent the relative production rate of each production site.

After processing the time series for each production site, combined time series were also generated for each manufacturer and for all domestic production sites. Due to substantial variations in production capacities and capacity utilization at the sites throughout the study period, a simple average was used instead of a weighted average when aggregating data at the manufacturer and national levels.

An analysis of average monthly production rates was conducted to further assess the indicator's ability to capture seasonal and monthly fluctuations in production levels. For this, the satellite-derived production estimates were grouped by calendar month, and the average production level for each month was calculated over the entire study period. This monthly aggregation aimed to identify consistent patterns or trends in production rates such as typical seasonal increases or decreases.

D. Validation of Results

As production data for the individual production sites is not publicly available, neither in daily nor temporally aggregated forms, as it is not released by the manufacturers, alternative data sources were required to approximate the performance of the Sentinel-1-derived production rates. For one, the German Association of the Automotive Industry (VDA) provides monthly aggregates of the total number of vehicles produced in Germany from January 2014 [20]. In addition, monthly production figures aggregated across all domestic production sites of each manufacturer were obtained from MarkLines, an information platform for the automotive industry that provides data on global vehicle production and sales based on aggregated data from various industry sources [21]. To ensure comparability between the VDA's monthly production figures, the MarkLines manufacturer-specific data, and the satellite-derived estimates of production parking lot utilization, the time series were rescaled to values between 0 and 1 using a min–max normalization approach. Pearson's correlation coefficients were calculated to assess the relationship between the normalized time series.

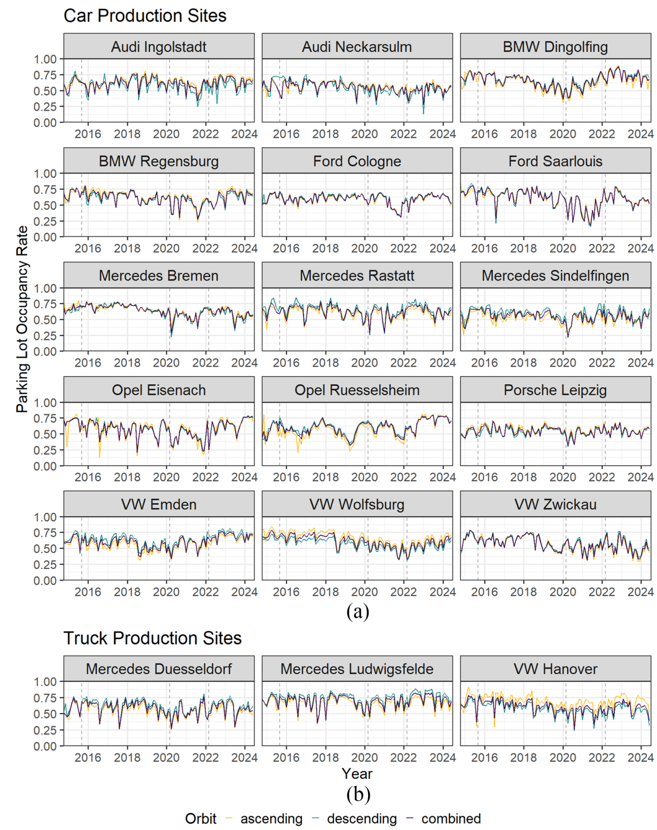

Fig. 4. Time series of average parking lot occupancy derived from the average monthly backscatter of each parking lot at the individual (a) car and (b) truck production sites, weighted according to the relative size of the respective parking lot. The vertical dashed lines indicate significant events for the industry: the revelation of the VW emissions scandal at the end of 2015, which caused significant financial and reputational losses leading to a decline in demand and a long-term strategic shift, and the duration of the COVID-19 pandemic in Germany from the first lockdown in March 2020 to the lifting of restrictions in March 2022, which caused significant disruptions in global supply chains and production halts.

III. Results

A. Site-Specific Production Parking Lot Occupancy

The time series of Sentinel-1 derived production parking lot occupancy rates, as depicted in Fig. 4, revealed significant fluctuations both between and within individual years at the vast majority of individual production sites. The degree of variability differed across sites: while production parking space occupancy at a few locations, such as Ford Cologne or Mercedes Bremen, remained relatively stable before the start of the COVID-19 pandemic in 2020, some locations, particularly those belonging to Opel, showed more pronounced fluctuations. Several locations, including the VW sites, saw a decline in occupancy after mid-2018. The influence of the COVID-19 pandemic and the associated countermeasures was more clearly evident, with sharp declines in parking lot occupancy at nearly all production

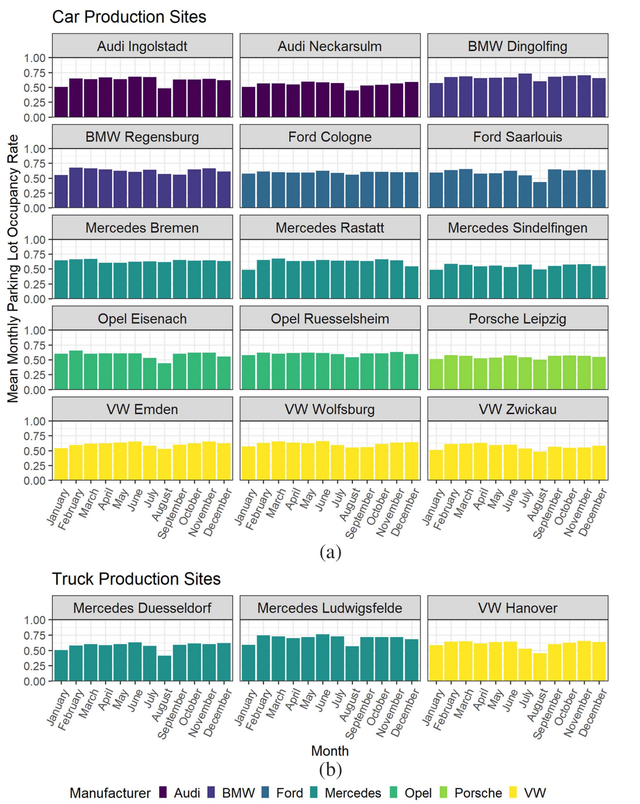

Fig. 5. Mean monthly production parking lot occupancy rates over the analyzed time period at the individual (a) car and (b) truck production sites.

TABLE III
OVERVIEW OF VALIDATION RESULTS

Manufacturer	Number of Sites	Vehicle Type	Pearson's Correlation Coefficient combined orbits	*ascending orbit*	*descending orbit*	Validation Data Source
Audi	2	Cars	0.35	*0.20*	*0.50*	MarkLines
BMW	2	Cars	0.50	*0.49*	*0.50*	MarkLines
Ford	2	Cars	0.58	*0.56*	*0.57*	MarkLines
Mercedes	3	Cars	0.61	*0.62*	*0.58*	MarkLines
	2	Trucks	0.22	*0.23*	*0.21*	MarkLines
Opel	2	Cars	0.30	*0.23*	*0.31*	MarkLines
Porsche	1	Cars	0.26	*0.24*	*0.25*	MarkLines
VW	3	Cars	0.69	*0.71*	*0.66*	MarkLines
	1	Trucks	0.57	*0.44*	*0.60*	MarkLines
All	**15**	**Cars**	**0.74**	***0.72***	***0.75***	**VDA**
	3	**Trucks**	**0.45**	***0.44***	***0.45***	**VDA**

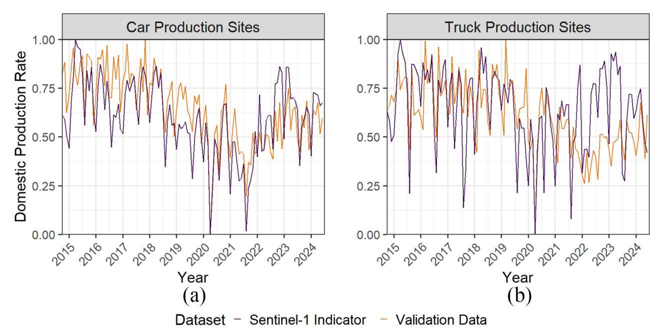

Fig. 6. Comparison of the satellite-based production indicator (purple lines) and the VDA validation data (orange lines) for the (a) car and (b) truck production sites aggregated for the entire domestic production.

facilities around the first lockdown in March 2020. The magnitude and duration of these drops varied across different sites. For example, occupancy at Mercedes Bremen was halved, while the decline was less pronounced at other sites like BMW Dingolfing or VW Emden with 10 to 15 percentage points. Following this initial drop, all facilities showed signs of recovery, though its pace and extent differed across sites. Throughout the pandemic, fluctuations became more pronounced at some sites like Ford Saarlouis, particularly towards the later stages. Many facilities experienced a second significant decline in occupancy rates in 2021, which, in some cases, such as at Ford Cologne, was even more severe than the first drop. Towards the end of the pandemic, most sites showed strong rebounds, with values approaching or even exceeding pre-pandemic levels. At VW's site in Zwickau, however, fluctuations were stronger than before 2020.

Despite the overall large variability in the time series, certain patterns emerged across the production sites, particularly concerning seasonal production cycles. At most sites, the mean occupancy per month over the entire time series was lower during the summer months of July and August, as well as the winter months of December and January (see Fig. 5).

While the time series data did not reveal distinct manufacturer-specific patterns, some manufacturers, such as VW and Mercedes, showed more commonalities in their occupancy rate fluctuations compared to others, such as Ford or BMW. For the different vehicle types, the truck production sites showed greater variations than the car production sites of the respective manufacturer.

With regard to the different satellite orbits, there were also no consistent patterns across the production sites. For some sites such as Ford's, the occupancy rates were almost identical across orbits while there were more pronounced differences at other sites like VW's Wolfsburg and Hanover (see Fig. 4).

B. Validation of Results

The overall correlation for the satellite-based indicator with production figures provided by the VDA across all manufacturers and sites was relatively strong at 0.74 considering all available data independent of the acquisition orbit (see Table III). For sites producing trucks, the correlation was moderate at 0.44. Manufacturer-specific correlations varied largely, with VW showing the highest correlation for both car (0.69) and truck (0.57) production. Mercedes exhibited a higher correlation for car production sites (0.61) but a lower correlation for facilities producing trucks (0.22). BMW and Ford displayed moderate correlations of 0.50 and 0.58, respectively, while Audi, Opel, and Porsche had lower correlations, ranging from 0.26 to 0.35. For most manufacturers, correlation differences between the time series acquired from ascending and descending orbits were negligible. For Audi and the VW truck sites, however, correlations were notably higher by up to 0.3 for the time series acquired from descending orbits.

The corresponding time series also show a close alignment for the domestic production rates determined from the Sentinel-1 data and the VDA data, with a slight tendency towards underestimation pre-pandemic and overestimation post-pandemic (see Fig. 6). The indicator was able to capture production patterns for some of the individual manufacturers, including BMW. Some satellite-derived time series, such as VW's or Audi's, showed

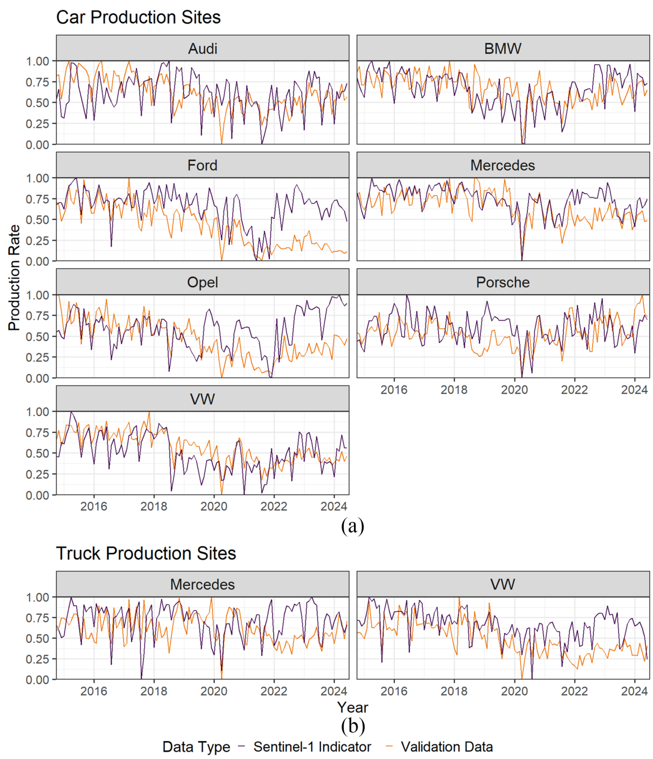

Fig. 7. Comparison of the normalized satellite-based production indicator (purple lines) and the MarkLines validation data (orange lines) for the (a) car and (b) truck production sites for each manufacturer.

more variability than the reference data. The comparison also revealed large discrepancies for the sites belonging to Ford and Opel before and after the start of the pandemic, where production rates were overestimated after 2020 (see Fig. 7). Overall, the indicator showed more variability for the sites producing trucks [see Figs. 6(b) and 7(b)].

IV. Discussion

A. Observations From the Sentinel-1 Derived Time Series

While all production sites exhibited different trends throughout the observation period, some recurring patterns emerged in the time series. This included notable increases or decreases in parking lot occupancy indicating seasonal production cycles and disruptive events. The indicator reproduced seasonal patterns consistent across multiple sites, with notable dips during the summer and winter months. These align with common site holidays during which the plants remain closed. However, capturing these production breaks based solely on parking lot occupancy proved challenging for a few individual sites and years. This difficulty likely arises because production halts do not necessarily imply empty parking lots as vehicles may still be stored temporarily until transportation resumes, depending on logistical schedules. The same holds true for production interruptions during the COVID-19 pandemic. Although all manufacturers faced disruptions due to lockdowns, not all time series, like those of Ford Cologne or Audi Ingolstadt, reflected the shutdowns. Meanwhile, the production interruption emerged clearly for all Mercedes and several other locations. Again, vehicles may have remained in the parking lots of some sites until work could resume, especially since transportation processes were similarly impacted during this time. Consequently, the indicator might struggle to capture sudden production pauses due to potential time lags between manufacturing halts and vehicle shipments. However, it is equally plausible that shipments are usually bundled, i.e., many vehicles are removed from the parking lots at the same time, and a satellite overpass shortly afterward could lead to an underestimation of current production volumes in other instances.

Despite these common patterns, differences between the production sites were more prevalent. For sites of the same manufacturer, this could be due to the production of different vehicle types and models for which demand may vary greatly, as well as to different production capacities and capacity utilization despite sharing similar production processes and cycles.

Deviations between the satellite-derived indicator and the production figures became notably more pronounced after 2022 for some of the manufacturers, especially Ford and Opel, which could indicate changes in transportation or other processes post-pandemic. This could be linked to the current capacity problem in automotive logistics that affects all transport routes. For road transportation, there is a shortage of trucks and drivers, as capacities have been reduced in recent years after declines in production. In the long term, manufacturers are aiming for a transition to a higher proportion of rail transport to reduce emissions, although this is also challenging due to a shortage of wagons and infrastructure in need of renovation [22]. However, without expert knowledge on how these lots are used at each site and other relevant processes, it remains difficult to interpret the results.

B. Quantitative Validation of the Indicator

Beyond these observations, it proved challenging to validate the indicator's performance quantitively, mainly due to the lack of site-specific production data. Instead, monthly production figures aggregated by manufacturer were used. However, a direct validation was possible for VW's Hanover plant with the available data as the manufacturer-level production data are split by produced vehicle type (i.e., cars and trucks) and VW only operates one domestic truck production site. For this site, the correlation with the validation data was nearly 0.6. In this case, the Sentinel-1 derived time series also aligned more closely with production figures before 2020, but tended to overestimate post-pandemic production levels [see Fig. 7(b)].

For the other sites, the monthly aggregates per manufacturer constrained the ability to fully validate the Sentinel-1-derived data. The use of aggregated data means that the correlations observed for a manufacturer may not accurately reflect the performance of the indicator at individual sites as it may obscure variations in production dynamics. High correlation values at the manufacturer level could mask poor performance at specific sites, while low correlations might hide sites where the indicator works well. This aggregation effect limits the ability to pinpoint the strengths and weaknesses of the indicator across different locations.

The analysis showed promising correlations with the production data for several of the manufacturers (BMW, Ford, Mercedes, and VW), but lower correlations for others (Audi, Opel, and Porsche). Performance may have been negatively affected for manufacturers like BMW and Porsche, where not all production sites could be included for various reasons (see Table II). The exclusion of certain sites from the analysis complicates the interpretation of correlation values, as the indicator does not fully represent the total production landscape for these manufacturers. Similarly, some parking lots had to be excluded at several sites as they were not consistent over the study period. The remaining lots may not provide a complete picture of production-related occupancy and might lead to an underestimation or overestimation of production volumes, depending on the role of the excluded lots in the overall production process. Continuous tracking and updating of parking lots regularly would be essential to ensure the continued accuracy of the indicator, particularly as facilities evolve.

While the results for the individual manufacturers vary largely, it should be noted that they do not contribute equally to national production. The highest correlation was achieved for VW with a correlation of 0.7. In 2023, the three VW car production sites included in this study accounted for nearly a quarter of the total domestic car production alone and can therefore already provide meaningful insights into the state of the industry. In contrast, the two Opel sites for example only represented around 4% of the total car production landscape.

Weighting locations by capacity was found to not be feasible for the validation of the domestic production time series, as the maximum capacities fluctuated over time and actual production rarely matches full capacity. As a result, the distribution of production volumes between sites varies annually. Despite these challenges, the correlation between the satellite-derived time series and the public production figures for cars was relatively strong at 0.74, underscoring its potential to provide meaningful insights into the state of the industry. For the sites producing trucks, the correlation was moderate at 0.45 as correlations were notably lower for the two Mercedes truck sites than VW Hanover.

C. Suitability of Production Parking Lot Occupancy As a Proxy for Production Levels

The quantitative validation with publicly available production figures was based on the hypothesis that production parking lot occupancy can serve as a proxy for production levels. However, as briefly highlighted previously, production parking lot occupancy does not always translate directly into the number of vehicles produced. Overall, the validation results indicate that there could be substantial differences in the relationship between production parking lot occupancy and production volumes, as the indicator overestimated production for some sites but captured it well for others. This resulted in correlations ranging from around 0.2 to 0.7. Several factors might contribute to these inconsistencies.

For example, there may be a lag between the production of vehicles and their transport to the production parking lots. This lag can be influenced by various operational factors, including the time it takes for vehicles to undergo quality checks or preparation for transport. Such delays could lead to discrepancies between the observed parking lot occupancy and actual production figures at any given time. In addition, it is unclear how long newly produced vehicles are stored in the production parking lots before they are scheduled for removal. As many parking lots are located near rails or have designated spaces for trucks used to transport the vehicles, the occupancy rates of these parking lots might be closer linked to transportation than production schedules. However, when focusing on the mean monthly production parking lot occupancy to analyze monthly production levels, some of these time lags might not be relevant.

Additionally, the presence of indoor storage facilities at some sites means that not all newly produced vehicles might be held in the monitored production parking lots. Vehicles could be stored indoors for various reasons, including protection from weather conditions or security concerns, which would not be captured by satellite observations of outdoor parking areas. Without expert knowledge, it is unclear which storage facilities might be prioritized. Furthermore, some monitored lots could be utilized for purposes other than storing new vehicles, such as temporarily storing vehicles with production defects before they are corrected. Defective vehicles may remain in these lots until repairs are completed, which can introduce additional variability in the occupancy rates that are not directly related to current production volumes. Similarly, objects other than vehicles, such as building materials during ongoing construction, could have been temporarily stored on the monitored lots, further complicating the interpretation of occupancy data.

D. Suitability of Sentinel-1 Data and Future Improvements

The results of this study additionally underline the suitability of the Sentinel-1 data for assessing parking lot occupancy. Unlike other industrial activities, remote sensing-based production monitoring of the German automotive industry is complex due to the focus on final assembly processes at the domestic sites. These likely do not generate clear heat signals, such as those used for previously mentioned economic indicators. Similarly, ongoing efforts to substantially reduce production-related emissions likely inhibit a direct link between emissions data and production activity. Therefore, this study explored deriving production parking lot occupancy at domestic automotive production sites from Sentinel-1 data as a real-time proxy for their production levels. Despite a spatial resolution where individual vehicles are not distinguishable, the mean backscatter values effectively captured broader occupancy trends. This approach holds several advantages over the use of very high resolution optical imagery to count individual cars in parking lots, including open data access and weather independence.

The primary limitations of the indicator likely stem from other factors rather than the use of Sentinel-1 data. In addition to the aspects discussed above, the temporal resolution also plays a role. Differences in orbit-dependent time series likely stem from the different acquisition dates within the respective months. Since Sentinel-1 provides imagery for each site only every few days, but parking lot occupancy can change quickly and it is not clear how long the cars usually remain there, changes in parking lot occupancy may not be fully captured. Therefore, the timing and frequency of satellite overpasses limits the ability to track production activities accurately, particularly if vehicle turnover rates are high or if there are brief production halts. In addition, data is not always acquired at uniform intervals, which could lead to uneven sampling of specific weekdays. This may introduce biases as production and transportation schedules likely differ on weekends, with truck driving bans in place on Sundays and public holidays in Germany. While the available data produced promising results for some plants even with limited data, increasing the number of observations could enhance robustness. Sentinel-1C will provide additional data points, potentially improving performance. At the same time, however, inconsistencies in the time series would remain due the time lag between data availability from Sentinel-1B and Sentinel-1C and the resulting differences in acquisition frequency throughout the observation period. This could potentially introduce biases or affect the continuity of trends across months or years.

Future research should explore the applicability of the developed methods to other economic sectors. For example, monitoring parking lot occupancy of supermarkets and retail stores could provide insights into consumer spending. This application would likely benefit from the availability of a larger number of data points due to the amount of relevant parking lots and from potential data fusion with existing complementary data sources, such as consumer sentiment indices. Similarly, tracking parking lot usage at airports could help assess trends in tourism and could be analyzed together with social media data, for example. Beyond parking lot analysis, the methodology could potentially also be adapted to analyze shipping volumes at major ports and supplement existing systems that monitor vessel movements, further extending its use for economic nowcasting.

V. Conclusion

To address the growing need for timely economic data, this study explored the development of an economic indicator estimating automotive production levels using Sentinel-1 data to track production parking lot occupancy at production sites in Germany. The indicator showed strong correlations of up to 0.7 with public production figures at key production sites, demonstrating its potential for providing near real-time economic insights into the state of the automotive industry despite inherent challenges in inferring production levels from parking lot occupancy alone. Nonetheless, insights from occupancy levels can be valuable for industry stakeholders in monitoring broader production trends and responding to changes, especially when the industry is facing significant uncertainties. Specifically, the method offers a novel tool for statistical offices to obtain near real-time data to complement traditional short-term macroeconomic indicators and enhance the timeliness of their economic estimates. For government agencies or policymakers, unexpected changes in production trends could indicate a potential need for support measures or other policy interventions.

While providing promising results for key production sites, the indicator also faced challenges reproducing the production levels of several individual sites, particularly struggling with accurately reflecting temporary production interruptions. This was likely due to the limited data availability and the dynamic nature of production sites. Without site-specific validation data for most sites, identifying the exact causes of these variations proved difficult. While incorporating additional data points in the future could enhance accuracy, continuous monitoring would require regular manual checks and updates of the parking lots. Especially in light of potential production scale-backs and site-closings in Germany, this would be essential to guarantee the reliability of the indicator.

Future research could transfer the developed methods to other key economic sectors, where Sentinel-1 based parking lot occupancy monitoring could provide relevant insights. Overall, this study demonstrates that openly available SAR data can complement traditional economic indicators, contributing to enhanced economic nowcasting. By providing timely insights into key industries, such approaches can support policymakers and other stakeholders in making informed decisions, especially amid economic uncertainties.

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