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A TWO-MODE SYSTEM FOR DIGITAL MATURITY ASSESSMENT OF AGRI-FOOD ENTERPRISES (ADMA)

The digitalization of Ukraine's agri-food sector is advancing unevenly and predominantly under the scenario of "light" digitalization – that is, the pointwise adoption of separate tools without a deep integration into the managerial loop of the enterprise [4]. This unevenness is reinforced by the structural heterogeneity of the sector: large agroholdings run the full three-tier digital route up to the construction of digital ecosystems grounded in artificial intelligence and machine learning, whereas smallholders are realistically capable only of a two-stage trajectory with a limited set of digital solutions [5]. Against this backdrop, managers require not an external benchmark but an instrument that quantifies the distance between the present state and the normative horizon across the functional subsystems of the enterprise. The Onion-S model sets that normative horizon in the form of a layered architecture around the production-technology core, yet taken on its own it remains a visual metaphor. Turning it into a working mechanism for strategic decisions requires an answer to one specific question: how to obtain a quantitative measure of an enterprise's digital maturity along each of these layers.

A systematization of the available maturity models based on CMMI, the Acatech Industrie 4.0 Maturity Index [1], the Deloitte Digital Maturity Model and the Digital Vortex shows that none of them is directly applicable in the agri-food sector. The reason lies not in the weakness of any particular model but in five systemic shortcomings characteristic of the whole class of instruments. The assessment is built from a single subject and does not scale to the supply chain or to the industry as a whole. The criteria carry a hidden industrial or telecommunications calibration that follows from their origin. The normative dimension is absent, although for Ukrainian producers correspondence with the acquis communautaire stands as a strategic reference point. The temporal dynamics do not take into account the seasonality and the multi-year investment cycles of livestock and crop production. The institutional context is taken out of the scope of analysis. These shortcomings are tightly intertwined with the broader theoretical framework of digital transformation [2] and with the sectoral specifics of digital agricultural production [3] described in the international literature. The ADMA assessment system (Agri-food Digital Maturity Assessment) is shaped as a response precisely to this five-component deficit.

In architectural terms, ADMA operates in two modes that measure one and the same digital maturity at different levels of aggregation. The subjective mode (S-mode) is implemented through the questioning of managers of a given enterprise on 19 statements grouped into 7 thematic blocks, scored on a Likert scale from 1 to 5. Blocks 1–5 assess the state of the core C and of the four operational layers L_1–L_4 of the Onion-S model. Block 6 measures the quality of the information flow I, and block 7 captures the strategic governance of digital transformation S. The statistical mode (St-mode) works at the meso- and macro-levels and draws on the annual state observation of Ukrstat under Form No. 1-ICT, together with the data of the NCEC and of the State GeoCadastre. The normalization of the statistical indicators is carried out by the min-max formula, with the reference maximum anchored not to a national "best" but to the value of the corresponding indicator in the EU leader country by the DESI score. The survey result of a given enterprise thus becomes interpretable within the coordinates of regional and national statistics, while the statistical view, in turn, gains its explanation through micro-level practices. The two modes function as a mutual context rather than as parallel assessment streams.

Unlike the widespread project template, in which the questionnaire is first designed and statistical analogues are then fitted to it, the ADMA approach begins from an inventory of the available statistical indicators. The structure of the accessible Ukrstat and DESI data has defined the thematic blocks of the questionnaire, and not the other way round. Each of the 19 statements has a fixed "statistical twin". The macro-indicator of the sector-wide coverage by ERP systems corresponds to the statement on the use of software for production planning. The indicator of the share of enterprises with digital traceability matches the statement on verified information regarding the origin of the product. This principle of vertical consistency removes a typical vulnerability of questionnaire-based instruments, where the self-assessment of an enterprise cannot be set against the official statistics of the industry.

The calculation of the integral digital maturity index (ADMI) is performed in four sequential operations. The primary scores on the Likert scale are linearly normalized into the range $[0; 1]$. For each layer the local indicators DMC, DML_1, DML_2, DML_3, DML_4 are computed as arithmetic means of the normalized statements of the corresponding block. In the same way DMI (information integration) and DMS (strategic governance) are obtained. At the next step the basic ADMI is formed as the arithmetic mean across the five operational layers. The equal weights in this formula are not a technical simplification but a direct mathematical expression of the first axiom of Onion-S. Since each layer acts as a necessary condition for realizing the potential of the others, none of them can claim a greater weight. The specificity of a particular enterprise manifests itself through the profile of the local indicators and not through a redistribution of weights in the formula.

The concluding step introduces a penalty coefficient based on the weakest-link principle: $\Pi = 1 - \alpha \times \max(0; \delta - \mathrm{DM}_{\min})$. Here α denotes the strength of the penalty, δ sets the threshold of critical weakness, and $\mathrm{DM}_{\min}$ is the minimum value among the local indicators. Under the condition $\mathrm{DM}_{\min} \geq \delta$ the penalty is not activated and $\Pi = 1$. The mechanism is a mathematical embodiment of the axiom of functional amplification. An enterprise with a failing logistics layer (for instance, $\mathrm{DML}_3 = 0.083$) ends up lower in the final ranking than an enterprise with a moderate but evenly distributed profile, even when the arithmetic mean of the local indicators is the same. The initial values $\alpha = 0.5$ and $\delta = 0.25$ are to be verified in a simulation experiment on 10,000 virtual enterprises with stochastically generated digital maturity profiles.

The ADMI obtained in this way is interpreted in terms of five discrete levels of maturity: analogue (0.00–0.20), fragmented (0.21–0.40), structured (0.41–0.60), integrated (0.61–0.80) and transformational (0.81–1.00). Each level corresponds to its own strategic pattern – from the elimination of failing layers at the fragmented level to the reinforcement of the core or an integration breakthrough at the structured level, depending on the profile of the local indicators. The static assessment is complemented by a dynamic dimension through the apparatus of Markov chains. The process $X(t)$, which reflects the level of digital maturity of an enterprise at an arbitrary moment in time, takes values from a finite set of five levels, while the matrix P defines the probabilities of transitions between them over a single step. The baseline assumption of tridiagonality of the matrix (a change of no more than one level per period) is extended to a pentadiagonal structure for large vertically integrated operators capable of digital leaps.

To sum up, ADMA offers a sector-specific measuring instrument that fills the methodological gap in the quantitative assessment of the digital transformation of agri-food systems – the gap on which the conclusions of contemporary theoretical [2; 3] and applied-sectoral studies [4; 5] converge. The two-mode architecture builds a through vertical of assessment linking the micro-level of the enterprise with the meso- and macro-levels of the sector. The ADMI formula with a penalty coefficient mathematically anchors the Onion-S axiom of functional amplification. The five-level scale turns the quantitative result into a basis for managerial choice. The correspondence of the 19 questionnaire statements with the indicators of Ukrstat and DESI makes the instrument transparent and compatible with the European system of digitalization monitoring. The parametric sensitivity of the model to α and δ, as well as the generation of scenario trajectories via Markov chains, are unfolded in a separate simulation model based on System Dynamics and constitute the subject of the next stage of the research.

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